7.1 Thread Basics

A ***thread*** is a single stream of control in the flow of a program. We initiate threads with a simple example:

Example 7.1 What are threads?

Consider the following code segment that computes the product of two dense matrices of size n x n.

```
1   for (row = 0; row < n; row++)
2       for (column = 0; column < n; column++)
3           c[row][column] =
4               dot_product(get_row(a, row),
5                           get_col(b, col));
```

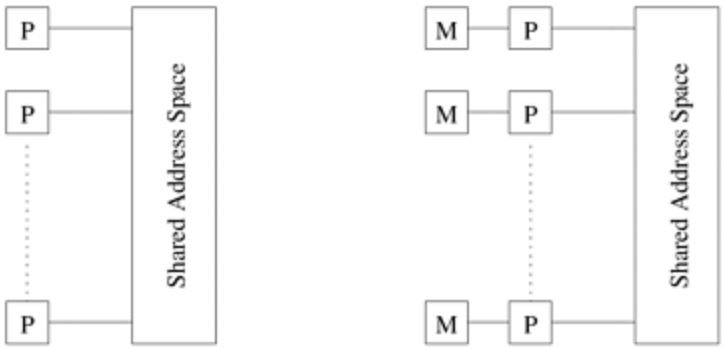
The `for` loop in this code fragment has n^2 iterations, each of which can be executed independently. Such an independent sequence of instructions is referred to as a thread. In the example presented above, there are n^2 threads, one for each iteration of the for-loop. Since each of these threads can be executed independently of the others, they can be scheduled concurrently on multiple processors. We can transform the above code segment as follows:

```
1   for (row = 0; row < n; row++)
2       for (column = 0; column < n; column++)
3           c[row][column] =
4               create_thread(dot_product(get_row(a, row),
5                                         get_col(b, col)));
```

Here, we use a function, `create_thread`, to provide a mechanism for specifying a C function as a thread. The underlying system can then schedule these threads on multiple processors. ■

Logical Memory Model of a Thread To execute the code fragment in Example 7.1 on multiple processors, each processor must have access to matrices a, b, and c. This is accomplished via a shared address space (described in Chapter 2). All memory in the logical machine model of a thread is globally accessible to every thread as illustrated in Figure 7.1(a). However, since threads are invoked as function calls, the stack corresponding to the function call is generally treated as being local to the thread. This is due to the liveness considerations of the stack. Since threads are scheduled at runtime (and no *a priori* schedule of their execution can be safely assumed), it is not possible to determine which stacks are live. Therefore, it is considered poor programming practice to treat stacks (thread-local variables) as global data. This implies a logical machine model illustrated in Figure 7.1(b), where memory modules M hold thread-local (stack allocated) data.

Figure 7.1. The logical machine model of a thread-based programming paradigm.



While this logical machine model gives the view of an equally accessible address space, physical realizations of this model deviate from this assumption. In distributed shared address space machines such as the Origin 2000, the cost to access a physically local memory may be an order of magnitude less than that of accessing remote memory. Even in architectures where the memory is truly equally accessible to all processors (such as shared bus architectures with global shared memory), the presence of caches with processors skews memory access time. Issues of locality of memory reference become important for extracting performance from such architectures.

7.2 Why Threads?

Threaded programming models offer significant advantages over message-passing programming models along with some disadvantages as well. Before we discuss threading APIs, let us briefly look at some of these.

Software Portability Threaded applications can be developed on serial machines and run on parallel machines without any changes. This ability to migrate programs between diverse architectural platforms is a very significant advantage of threaded APIs. It has implications not just for software utilization but also for application development since supercomputer time is often scarce and expensive.

Latency Hiding One of the major overheads in programs (both serial and parallel) is the access latency for memory access, I/O, and communication. By allowing multiple threads to execute on the same processor, threaded APIs enable this latency to be hidden (as seen in Chapter 2). In effect, while one thread is waiting for a communication operation, other threads can utilize the CPU, thus masking associated overhead.

Scheduling and Load Balancing While writing shared address space parallel programs, a programmer must express concurrency in a way that minimizes overheads of remote interaction and idling. While in many structured applications the task of allocating equal work to processors is easily accomplished, in unstructured and dynamic applications (such as game playing and discrete optimization) this task is more difficult. Threaded APIs allow the programmer to specify a large number of concurrent tasks and support system-level dynamic mapping of tasks to processors with a view to minimizing idling overheads. By providing this support at the system level, threaded APIs rid the programmer of the burden of explicit scheduling and load balancing.

Ease of Programming, Widespread Use Due to the aforementioned advantages, threaded programs are significantly easier to write than corresponding programs using message passing APIs. Achieving identical levels of performance for the two programs may require additional effort, however. With widespread acceptance of the POSIX thread API, development tools for POSIX threads are more widely available and stable. These issues are important from the program development and software engineering aspects.

7.10 OpenMP: a Standard for Directive Based Parallel Programming

In the first part of this chapter, we studied the use of threaded APIs for programming shared address space machines. While standardization and support for these APIs has come a long way, their use is still predominantly restricted to system programmers as opposed to application programmers. One of the reasons for this is that APIs such as Pthreads are considered to be low-level primitives. Conventional wisdom indicates that a large class of applications can be efficiently supported by higher level constructs (or directives) which rid the programmer of the mechanics of manipulating threads. Such directive-based languages have existed for a long time, but only recently have standardization efforts succeeded in the form of OpenMP. OpenMP is an API that can be used with FORTRAN, C, and C++ for programming shared address space machines. OpenMP directives provide support for concurrency, synchronization, and data handling while obviating the need for explicitly setting up mutexes, condition variables, data scope, and initialization. We use the OpenMP C API in the rest of this chapter.

7.10.1 The OpenMP Programming Model

We initiate the OpenMP programming model with the aid of a simple program. OpenMP directives in C and C++ are based on the `#pragma` compiler directives. The directive itself consists of a directive name followed by clauses.

```
1   #pragma omp directive [clause list]
```

OpenMP programs execute serially until they encounter the `parallel` directive. This directive is responsible for creating a group of threads. The exact number of threads can be specified in the directive, set using an environment variable, or at runtime using OpenMP functions. The main thread that encounters the `parallel` directive becomes the ***master*** of this group of threads and is assigned the thread id 0 within the group. The `parallel` directive has the following prototype:

```
1   #pragma omp parallel [clause list]
2   /* structured block */
3
```

Each thread created by this directive executes the `structured block` specified by the parallel directive. The clause list is used to specify conditional parallelization, number of threads, and data handling.

- **Conditional Parallelization:** The clause `if (scalar expression)` determines whether the parallel construct results in creation of threads. Only one `if` clause can be used with a parallel directive.

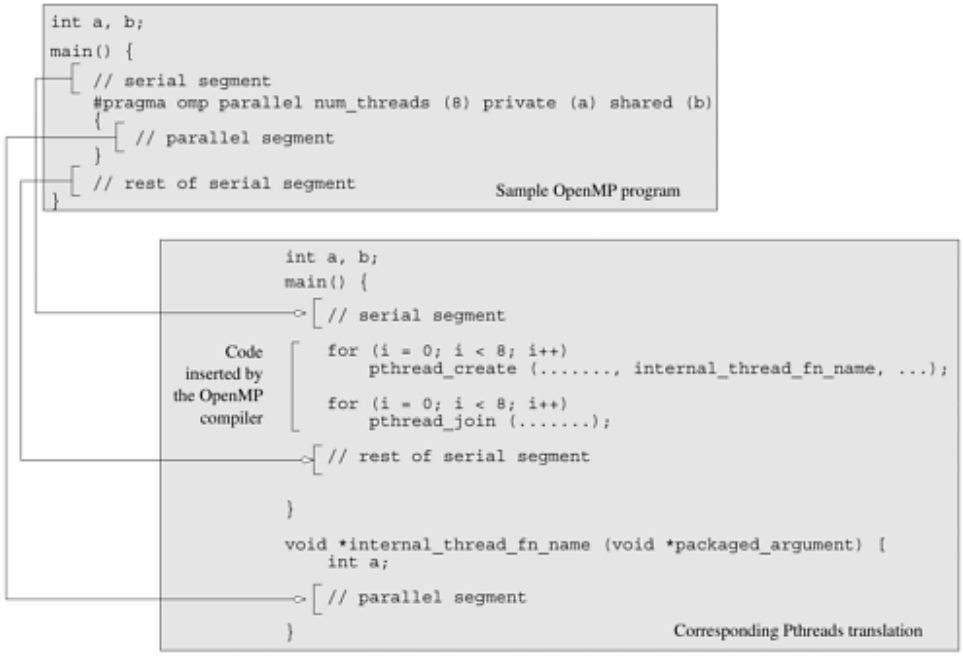
- **Degree of Concurrency:** The clause `num_threads (integer expression)` specifies the number of threads that are created by the `parallel` directive.

- **Data Handling:** The clause `private (variable list)` indicates that the set of variables specified is local to each thread  i.e., each thread has its own copy of

each variable in the list. The clause `firstprivate (variable list)` is similar to the private clause, except the values of variables on entering the threads are initialized to corresponding values before the parallel directive. The clause shared (variable list) indicates that all variables in the list are shared across all the threads, i.e., there is only one copy. Special care must be taken while handling these variables by threads to ensure serializability.

It is easy to understand the concurrency model of OpenMP when viewed in the context of the corresponding Pthreads translation. In Figure 7.4, we show one possible translation of an OpenMP program to a Pthreads program. The interested reader may note that such a translation can easily be automated through a Yacc or CUP script.

Figure 7.4. A sample OpenMP program along with its Pthreads translation that might be performed by an OpenMP compiler.



Example 7.9 Using the parallel directive

```
1   #pragma omp parallel if (is_parallel == 1) num_threads(8) \
2                       private (a) shared (b) firstprivate(c)
3   {
4       /* structured block */
5   }
```

Here, if the value of the variable `is_parallel` equals one, eight threads are created. Each of these threads gets private copies of variables `a` and `c`, and shares a single value of variable `b`. Furthermore, the value of each copy of `c` is initialized to the value of `c` before the parallel directive. ■

The default state of a variable is specified by the clause `default (shared)` or `default (none)`. The clause `default (shared)` implies that, by default, a variable is shared by all the threads. The clause `default (none)` implies that the state of each variable used in a thread must be explicitly specified. This is generally recommended, to guard against errors arising from unintentional concurrent access to shared data.

Just as `firstprivate` specifies how multiple local copies of a variable are initialized inside a thread, the `reduction` clause specifies how multiple local copies of a variable at different threads are combined into a single copy at the master when threads exit. The usage of the `reduction` clause is `reduction (operator: variable list)`. This clause performs a reduction on the scalar variables specified in the list using the `operator`. The variables in the list are implicitly specified as being private to threads. The `operator` can be one of `+, *, -, &, |, ^, &&`, and `||`.

Example 7.10 Using the reduction clause

```
1       #pragma omp parallel reduction(+: sum) num_threads(8)
2       {
3           /* compute local sums here */
4       }
5       /* sum here contains sum of all local instances of sums */
```

In this example, each of the eight threads gets a copy of the variable `sum`. When the threads exit, the sum of all of these local copies is stored in the single copy of the variable (at the master thread). ■

In addition to these data handling clauses, there is one other clause, `copyin`. We will describe this clause in Section 7.10.4 after we discuss data scope in greater detail.

We can now use the `parallel` directive along with the clauses to write our first OpenMP program. We introduce two functions to facilitate this. The `omp_get_num_threads()` function returns the number of threads in the parallel region and the `omp_get_thread_num()` function returns the integer i.d. of each thread (recall that the master thread has an i.d. 0).

Example 7.11 Computing PI using OpenMP directives

Our first OpenMP example follows from Example 7.2, which presented a Pthreads program for the same problem. The parallel directive specifies that all variables except `npoints`, the total number of random points in two dimensions across all threads, are local. Furthermore, the directive specifies that there are eight threads, and the value of `sum` after all threads complete execution is the sum of local values at each thread. The function `omp_get_num_threads` is used to determine the total number of threads. As in Example 7.2, a `for` loop generates the required number of random points (in two dimensions) and determines how many of them are within the prescribed circle of unit diameter.

```
1   /* ********************************************************
2      An OpenMP version of a threaded program to compute PI.
3      ******************************************************** */
4
```

```
5       #pragma omp parallel default(private) shared (npoints) \
6                            reduction(+: sum) num_threads(8)
7       {
8         num_threads = omp_get_num_threads();
9         sample_points_per_thread = npoints / num_threads;
10        sum = 0;
11        for (i = 0; i < sample_points_per_thread; i++) {
12          rand_no_x =(double)(rand_r(&seed))/(double)((2<<14)-1);
13          rand_no_y =(double)(rand_r(&seed))/(double)((2<<14)-1);
14          if (((rand_no_x - 0.5) * (rand_no_x - 0.5) +
15              (rand_no_y - 0.5) * (rand_no_y - 0.5)) < 0.25)
16              sum ++;
17        }
18      }
```

■

Note that this program is much easier to write in terms of specifying creation and termination of threads compared to the corresponding POSIX threaded program.

7.10.2 Specifying Concurrent Tasks in OpenMP

The `parallel` directive can be used in conjunction with other directives to specify concurrency across iterations and tasks. OpenMP provides two directives – `for` and `sections` – to specify concurrent iterations and tasks.

The `for` Directive

The `for` directive is used to split parallel iteration spaces across threads. The general form of a `for` directive is as follows:

```
1       #pragma omp for [clause list]
2           /* for loop */
3
```

The clauses that can be used in this context are: `private`, `firstprivate`, `lastprivate`, `reduction`, `schedule`, `nowait`,and`ordered`. The first four clauses deal with data handling and have identical semantics as in the case of the `parallel` directive. The `lastprivate` clause deals with how multiple local copies of a variable are written back into a single copy at the end of the parallel `for` loop. When using a `for` loop (or `sections` directive as we shall see) for farming work to threads, it is sometimes desired that the last iteration (as defined by serial execution) of the `for` loop update the value of a variable. This is accomplished using the `lastprivate` directive.

Example 7.12 Using the for directive for computing p

Recall from Example 7.11 that each iteration of the `for` loop is independent, and can be executed concurrently. In such situations, we can simplify the program using the `for`

directive. The modified code segment is as follows:

```
1     #pragma omp parallel default(private) shared (npoints) \
2                          reduction(+: sum) num_threads(8)
3     {
4       sum=0;
5       #pragma omp for
6       for (i = 0; i < npoints; i++) {
7         rand_no_x =(double)(rand_r(&seed))/(double)((2<<14)-1);
8         rand_no_y =(double)(rand_r(&seed))/(double)((2<<14)-1);
9         if (((rand_no_x - 0.5) * (rand_no_x - 0.5) +
10            (rand_no_y - 0.5) * (rand_no_y - 0.5)) < 0.25)
11            sum ++;
12      }
13    }
```

The `for` directive in this example specifies that the `for` loop immediately following the directive must be executed in parallel, i.e., split across various threads. Notice that the loop index goes from 0 to `npoints` in this case, as opposed to `sample_points_per_thread` in Example 7.11. The loop index for the `for` directive is assumed to be private, by default. It is interesting to note that the only difference between this OpenMP segment and the corresponding serial code is the two directives. This example illustrates how simple it is to convert many serial programs into OpenMP-based threaded programs. ■

Assigning Iterations to Threads

The `schedule` clause of the `for` directive deals with the assignment of iterations to threads. The general form of the `schedule` directive is `schedule(scheduling_class[, parameter])`. OpenMP supports four scheduling classes: `static`, `dynamic`, `guided`, and `runtime`.

Example 7.13 Scheduling classes in OpenMP – matrix multiplication.

We explore various scheduling classes in the context of dense matrix multiplication. The code for multiplying two matrices `a` and `b` to yield matrix `c` is as follows:

```
1       for (i = 0; i < dim; i++) {
2           for (j = 0; j < dim; j++) {
3               c(i,j) = 0;
4               for (k = 0; k < dim; k++) {
5                   c(i,j) += a(i, k) * b(k, j);
6               }
7           }
8       }
```

The code segment above specifies a three-dimensional iteration space providing us with an ideal example for studying various scheduling classes in OpenMP. ■

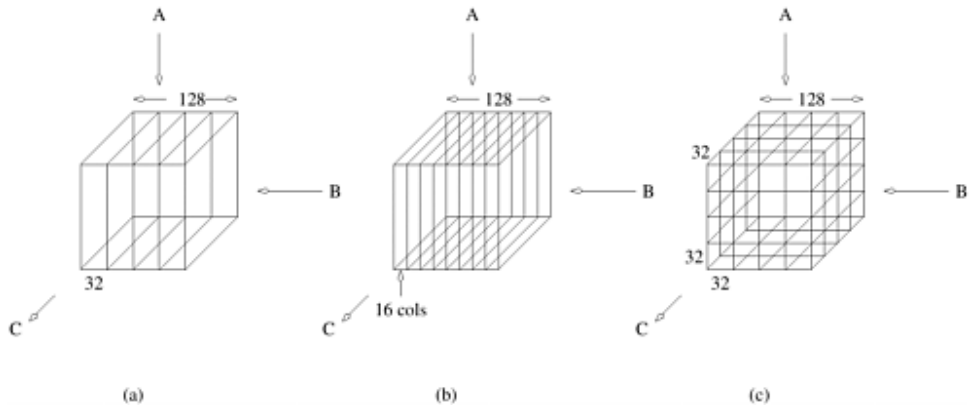
Static The general form of the `static` scheduling class is `schedule(static[, chunk-size])`. This technique splits the iteration space into equal chunks of size `chunk-size` and assigns them to threads in a round-robin fashion. When no `chunk-size` is specified, the iteration space is split into as many chunks as there are threads and one chunk is assigned to each thread.

Example 7.14 Static scheduling of loops in matrix multiplication

The following modification of the matrix-multiplication program causes the outermost iteration to be split statically across threads as illustrated in Figure 7.5(a).

```
1   #pragma omp parallel default(private) shared (a, b, c, dim) \
2                        num_threads(4)
3       #pragma omp for schedule(static)
4       for (i = 0; i < dim; i++) {
5           for (j = 0; j < dim; j++) {
6               c(i,j) = 0;
7               for (k = 0; k < dim; k++) {
8                   c(i,j) += a(i, k) * b(k, j);
9               }
10          }
11      }
```

Figure 7.5. Three different schedules using the static scheduling class of OpenMP.



Since there are four threads in all, if `dim = 128`, the size of each partition is 32 columns, since we have not specified the chunk size. Using `schedule(static, 16)` results in the partitioning of the iteration space illustrated in Figure 7.5(b). Another example of the split illustrated in Figure 7.5(c) results when each `for` loop in the program in Example 7.13 is parallelized across threads with a `schedule(static)` and nested parallelism is enabled (see Section 7.10.6). ■

Dynamic Often, because of a number of reasons, ranging from heterogeneous computing resources to non-uniform processor loads, equally partitioned workloads take widely varying execution times. For this reason, OpenMP has a `dynamic` scheduling class. The general form of this class is `schedule(dynamic[, chunk-size])`. The iteration space is partitioned into chunks given by `chunk-size`. However, these are assigned to threads as they become idle. This takes care of the temporal imbalances resulting from static scheduling. If no `chunk-size` is specified, it defaults to a single iteration per chunk.

Guided Consider the partitioning of an iteration space of 100 iterations with a chunk size of 5. This corresponds to 20 chunks. If there are 16 threads, in the best case, 12 threads get one chunk each and the remaining four threads get two chunks. Consequently, if there are as many processors as threads, this assignment results in considerable idling. The solution to this problem (also referred to as an ***edge effect***) is to reduce the chunk size as we proceed through the computation. This is the principle of the `guided` scheduling class. The general form of this class is `schedule(guided[, chunk-size])`.In this class, the chunk size is reduced exponentially as each chunk is dispatched to a thread. The `chunk-size` refers to the smallest chunk that should be dispatched. Therefore, when the number of iterations left is less than `chunk-size`, the entire set of iterations is dispatched at once. The value of `chunk-size` defaults to one if none is specified.

Runtime Often it is desirable to delay scheduling decisions until runtime. For example, if one would like to see the impact of various scheduling strategies to select the best one, the scheduling can be set to `runtime`. In this case the environment variable `OMP_SCHEDULE` determines the scheduling class and the chunk size.

When no scheduling class is specified with the `omp for` directive, the actual scheduling technique is not specified and is implementation dependent. The `for` directive places additional restrictions on the `for` loop that follows. For example, it must not have a break statement, the loop control variable must be an integer, the initialization expression of the `for` loop must be an integer assignment, the logical expression must be one of <, $\leq$, >, or $\geq$, and the increment expression must have integer increments or decrements only. For more details on these restrictions, we refer the reader to the OpenMP manuals.

Synchronization Across Multiple `for` Directives

Often, it is desirable to have a sequence of `for`-directives within a parallel construct that do not execute an implicit barrier at the end of each `for` directive. OpenMP provides a clause `nowait`, which can be used with a `for` directive to indicate that the threads can proceed to the next statement without waiting for all other threads to complete the `for` loop execution. This is illustrated in the following example:

Example 7.15 Using the nowait clause

Consider the following example in which variable `name` needs to be looked up in two lists `current_list` and `past_list`. If the name exists in a list, it must be processed accordingly. The name might exist in both lists. In this case, there is no need to wait for all threads to complete execution of the first loop before proceeding to the second loop. Consequently, we can use the `nowait` clause to save idling and synchronization overheads as follows:

```
1       #pragma omp parallel
2       {
3           #pragma omp for nowait
4               for (i = 0; i < nmax; i++)
5                   if (isEqual(name, current_list[i])
6                       processCurrentName(name);
7           #pragma omp for
8               for (i = 0; i < mmax; i++)
9                   if (isEqual(name, past_list[i])
10                      processPastName(name);
11      }
```

■

The `sections` Directive

The `for` directive is suited to partitioning iteration spaces across threads. Consider now a scenario in which there are three tasks (`taskA`, `taskB`, and `taskC`) that need to be executed. Assume that these tasks are independent of each other and therefore can be assigned to different threads. OpenMP supports such non-iterative parallel task assignment using the `sections` directive. The general form of the `sections` directive is as follows:

```
1   #pragma omp sections [clause list]
2   {
3       [#pragma omp section
4           /* structured block */
5       ]
6       [#pragma omp section
7           /* structured block */
8       ]
9       ...
10  }
```

This `sections` directive assigns the structured block corresponding to each section to one thread (indeed more than one section can be assigned to a single thread). The `clause list` may include the following clauses – `private`, `firstprivate`, `lastprivate`, `reduction`, and `no wait`. The syntax and semantics of these clauses are identical to those in the case of the `for` directive. The `lastprivate` clause, in this case, specifies that the last section (lexically) of the `sections` directive updates the value of the variable. The `nowait` clause specifies that there is no implicit synchronization among all threads at the end of the `sections` directive.

For executing the three concurrent tasks `taskA`, `taskB`, and `taskC`, the corresponding `sections` directive is as follows:

```
1       #pragma omp parallel
2       {
3           #pragma omp sections
4           {
```

```
5               #pragma omp section
6               {
7                   taskA();
8               }
9               #pragma omp section
10              {
11                  taskB();
12              }
13              #pragma omp section
14              {
15                  taskC();
16              }
17          }
18      }
```

If there are three threads, each section (in this case, the associated task) is assigned to one thread. At the end of execution of the assigned section, the threads synchronize (unless the `nowait` clause is used). Note that it is illegal to branch in and out of `section` blocks.

Merging Directives

In our discussion thus far, we use the directive `parallel` to create concurrent threads, and `for` and `sections` to farm out work to threads. If there was no `parallel` directive specified, the `for` and `sections` directives would execute serially (all work is farmed to a single thread, the master thread). Consequently, `for` and `sections` directives are generally preceded by the `parallel` directive. OpenMP allows the programmer to merge the `parallel` directives to `parallel for` and `parallel sections`, re-spectively. The clause list for the merged directive can be from the clause lists of either the `parallel` or `for / sections` directives.

For example:

```
1       #pragma omp parallel default (private) shared (n)
2       {
3           #pragma omp for
4           for (i = 0 < i < n; i++) {
5           /* body of parallel for loop */
6           }
7       }
```

is identical to:

```
1   #pragma omp parallel for default (private) shared (n)
2   {
3       for (i = 0 < i < n; i++) {
4       /* body of parallel for loop */
5       }
6   }
7
```

and:

```
1       #pragma omp parallel
2       {
3           #pragma omp sections
4           {
5               #pragma omp section
6               {
7                   taskA();
8               }
9               #pragma omp section
10              {
11                 taskB();
12              }
13              /* other sections here */
14          }
15      }
```

is identical to:

```
1       #pragma omp parallel sections
2       {
3           #pragma omp section
4           {
5               taskA();
6           }
7           #pragma omp section
8           {
9               taskB();
10          }
11          /* other sections here */
12      }
```

Nesting `parallel` Directives

Let us revisit Program 7.13. To split each of the `for` loops across various threads, we would modify the program as follows:

```
1   #pragma omp parallel for default(private) shared (a, b, c, dim) \
2                       num_threads(2)
3       for (i = 0; i < dim; i++) {
4       #pragma omp parallel for default(private) shared (a, b, c, dim) \
5                       num_threads(2)
6           for (j = 0; j < dim; j++) {
7               c(i,j) = 0;
8               #pragma omp parallel for default(private) \
9                       shared (a, b, c, dim) num_threads(2)
10              for (k = 0; k < dim; k++) {
11                  c(i,j) += a(i, k) * b(k, j);
12              }
13          }
14      }
```

We start by making a few observations about how this segment is written. Instead of nesting three `for` directives inside a single `parallel` directive, we have used three `parallel for` directives. This is because OpenMP does not allow `for`, `sections`, and

`single` directives that bind to the same `parallel` directive to be nested. Furthermore, the code as written only generates a logical team of threads on encountering a nested `parallel` directive. The newly generated logical team is still executed by the same thread corresponding to the outer `parallel` directive. To generate a new set of threads, nested parallelism must be enabled using the `OMP_NESTED` environment variable. If the `OMP_NESTED` environment variable is set to `FALSE`, then the inner `parallel` region is serialized and executed by a single thread. If the `OMP_NESTED` environment variable is set to `TRUE`, nested parallelism is enabled. The default state of this environment variable is `FALSE`, i.e., nested parallelism is disabled. OpenMP environment variables are discussed in greater detail in Section 7.10.6.

There are a number of other restrictions associated with the use of synchronization constructs in nested parallelism. We refer the reader to the OpenMP manual for a discussion of these restrictions.

7.10.3 Synchronization Constructs in OpenMP

In Section 7.5, we described the need for coordinating the execution of multiple threads. This may be the result of a desired execution order, the atomicity of a set of instructions, or the need for serial execution of code segments. The Pthreads API supports mutexes and condition variables. Using these we implemented a range of higher level functionality in the form of read-write locks, barriers, monitors, etc. The OpenMP standard provides this high-level functionality in an easy-to-use API. In this section, we will explore these directives and their use.

Synchronization Point: The `barrier` Directive

A barrier is one of the most frequently used synchronization primitives. OpenMP provides a `barrier` directive, whose syntax is as follows:

```
1       #pragma omp barrier
```

On encountering this directive, all threads in a team wait until others have caught up, and then release. When used with nested `parallel` directives, the `barrier` directive binds to the closest `parallel` directive. For executing barriers conditionally, it is important to note that a `barrier` directive must be enclosed in a compound statement that is conditionally executed. This is because pragmas are compiler directives and not a part of the language. Barriers can also be effected by ending and restarting `parallel` regions. However, there is usually a higher overhead associated with this. Consequently, it is not the method of choice for implementing barriers.

Single Thread Executions: The `single` and `master` Directives

Often, a computation within a parallel section needs to be performed by just one thread. A simple example of this is the computation of the mean of a list of numbers. Each thread can compute a local sum of partial lists, add these local sums to a shared global sum, and have one thread compute the mean by dividing this global sum by the number of entries in the list. The last step can be accomplished using a `single` directive.

A `single` directive specifies a structured block that is executed by a single (arbitrary) thread. The syntax of the `single` directive is as follows:

```
1   #pragma omp single [clause list]
2            structured block
```

The clause list can take clauses `private`, `firstprivate`, and `nowait`. These clauses have the same semantics as before. On encountering the `single` block, the first thread enters the block. All the other threads proceed to the end of the block. If the `nowait` clause has been specified at the end of the block, then the other threads proceed; otherwise they wait at the end of the `single` block for the thread to finish executing the block. This directive is useful for computing global data as well as performing I/O.

The `master` directive is a specialization of the `single` directive in which only the master thread executes the structured block. The syntax of the `master` directive is as follows:

```
1   #pragma omp master
2            structured block
```

In contrast to the `single` directive, there is no implicit barrier associated with the `master` directive.

Critical Sections: The `critical` and `atomic` Directives

In our discussion of Pthreads, we had examined the use of locks to protect critical regions – regions that must be executed serially, one thread at a time. In addition to explicit lock management (Section 7.10.5), OpenMP provides a `critical` directive for implementing critical regions. The syntax of a `critical` directive is:

```
1   #pragma omp critical [(name)]
2            structured block
```

Here, the optional identifier `name` can be used to identify a critical region. The use of `name` allows different threads to execute different code while being protected from each other.

Example 7.16 Using the critical directive for producer-consumer threads

Consider a producer-consumer scenario in which a producer thread generates a task and inserts it into a task-queue. The consumer thread extracts tasks from the queue and executes them one at a time. Since there is concurrent access to the task-queue, these accesses must be serialized using critical blocks. Specifically, the tasks of inserting and extracting from the task-queue must be serialized. This can be implemented as follows:

```
1       #pragma omp parallel sections
2       {
3           #pragma parallel section
4           {
5               /* producer thread */
6               task = produce_task();
7               #pragma omp critical ( task_queue)
8               {
9                   insert_into_queue(task);
10              }
11          }
```

```
12          #pragma parallel section
13          {
14              /* consumer thread */
15              #pragma omp critical ( task_queue)
16              {
17                  task = extract_from_queue(task);
18              }
19              consume_task(task);
20          }
21      }
```

Note that queue full and queue empty conditions must be explicitly handled here in functions `insert_into_queue` and `extract_from_queue`. ■

The `critical` directive ensures that at any point in the execution of the program, only one thread is within a critical section specified by a certain name. If a thread is already inside a critical section (with a name), all others must wait until it is done before entering the named critical section. The name field is optional. If no name is specified, the critical section maps to a default name that is the same for all unnamed critical sections. The names of critical sections are global across the program.

It is easy to see that the `critical` directive is a direct application of the corresponding `mutex` function in Pthreads. The name field maps to the name of the mutex on which the lock is performed. As is the case with Pthreads, it is important to remember that `critical` sections represent serialization points in the program and therefore we must reduce the size of the critical sections as much as possible (in terms of execution time) to get good performance.

There are some obvious safeguards that must be noted while using the `critical` directive. The `block` of instructions must represent a structured block, i.e., no jumps are permitted into or out of the block. It is easy to see that the former would result in non-critical access and the latter in an unreleased lock, which could cause the threads to wait indefinitely.

Often, a critical section consists simply of an update to a single memory location, for example, incrementing or adding to an integer. OpenMP provides another directive, `atomic`, for such atomic updates to memory locations. The `atomic` directive specifies that the memory location update in the following instruction should be performed as an atomic operation. The update instruction can be one of the following forms:

```
1   x binary_operation = expr
2   x++
3   ++x
4   x--
5   --x
```

Here, `expr` is a scalar expression that does not include a reference to `x`, `x` itself is an lvalue of scalar type, and `binary_operation` is one of {+, *, -, /, &, ′||, ≪, ≫,}. It is important to note that the `atomic` directive only atomizes the load and store of the scalar variable. The evaluation of the expression is not atomic. Care must be taken to ensure that there are no race conditions hidden therein. This also explains why the `expr`

term in the `atomic` directive cannot contain the updated variable itself. All `atomic` directives can be replaced by `critical` directives provided they have the same name. However, the availability of atomic hardware instructions may optimize the performance of the program, compared to translation to `critical` directives.

In-Order Execution: The `ordered` Directive

In many circumstances, it is necessary to execute a segment of a parallel loop in the order in which the serial version would execute it. For example, consider a `for` loop in which, at some point, we compute the cumulative sum in array `cumul_sum` of a list stored in array `list`. The array `cumul_sum` can be computed using a `for` loop over index `i` serially by executing `cumul_sum[i] = cumul_sum[i-1] + list[i]`. When executing this `for` loop across threads, it is important to note that `cumul_sum[i]` can be computed only after `cumul_sum[i-1]` has been computed. Therefore, the statement would have to executed within an `ordered` block.

The syntax of the `ordered` directive is as follows:

```
1   #pragma omp ordered
2       structured block
```

Since the `ordered` directive refers to the in-order execution of a `for` loop, it must be within the scope of a `for` or `parallel for` directive. Furthermore, the `for` or `parallel for` directive must have the `ordered` clause specified to indicate that the loop contains an `ordered` block.

Example 7.17 Computing the cumulative sum of a list using the ordered directive

As we have just seen, to compute the cumulative sum of `i` numbers of a list, we can add the current number to the cumulative sum of `i-1` numbers of the list. This loop must, however, be executed in order. Furthermore, the cumulative sum of the first element is simply the element itself. We can therefore write the following code segment using the `ordered` directive.

```
1       cumul_sum[0] = list[0];
2       #pragma omp parallel for private (i) \
3                   shared (cumul_sum, list, n) ordered
4       for (i = 1; i < n; i++)
5       {
6           /* other processing on list[i] if needed */
7
8           #pragma omp ordered
9           {
10              cumul_sum[i] = cumul_sum[i-1] + list[i];
11          }
12      }
```

■

It is important to note that the `ordered` directive represents an ordered serialization point in the program. Only a single thread can enter an ordered block when all prior threads (as determined by loop indices) have exited. Therefore, if large portions of a loop are enclosed in `ordered` directives, corresponding speedups suffer. In the above example, the parallel formulation is expected to be no faster than the serial formulation unless there is significant processing associated with `list[i]` outside the `ordered` directive. A single `for` directive is constrained to have only one `ordered` block in it.

Memory Consistency: The `flush` Directive

The `flush` directive provides a mechanism for making memory consistent across threads. While it would appear that such a directive is superfluous for shared address space machines, it is important to note that variables may often be assigned to registers and register-allocated variables may be inconsistent. In such cases, the `flush` directive provides a memory fence by forcing a variable to be written to or read from the memory system. All write operations to shared variables must be committed to memory at a flush and all references to shared variables after a fence must be satisfied from the memory. Since private variables are relevant only to a single thread, the `flush` directive applies only to shared variables.

The syntax of the `flush` directive is as follows:

```
1   #pragma omp flush[(list)]
```

The optional list specifies the variables that need to be flushed. The default is that all shared variables are flushed.

Several OpenMP directives have an implicit `flush`. Specifically, a `flush` is implied at a `barrier`, at the entry and exit of `critical`, `ordered`, `parallel`, `parallel for`, and `parallel sections` blocks and at the exit of `for`, `sections`, and `single` blocks. A `flush` is not implied if a `nowait` clause is present. It is also not implied at the entry of `for`, `sections`, and `single` blocks and at entry or exit of a `master` block.

7.10.4 Data Handling in OpenMP

One of the critical factors influencing program performance is the manipulation of data by threads. We have briefly discussed OpenMP support for various data classes such as `private`, `shared`, `firstprivate`, and `lastprivate`. We now examine these in greater detail, with a view to understanding how these classes should be used. We identify the following heuristics to guide the process:

- If a thread initializes and uses a variable (such as loop indices) and no other thread accesses the data, then a local copy of the variable should be made for the thread. Such data should be specified as `private`.

- If a thread repeatedly reads a variable that has been initialized earlier in the program, it is beneficial to make a copy of the variable and inherit the value at the time of thread creation. This way, when a thread is scheduled on the processor, the data can reside at the same processor (in its cache if possible) and accesses will not result in interprocessor communication. Such data should be specified as `firstprivate`.

- If multiple threads manipulate a single piece of data, one must explore ways of breaking these manipulations into local operations followed by a single global operation. For example, if multiple threads keep a count of a certain event, it is beneficial to keep local counts and to subsequently accrue it using a single summation at the end of the parallel block. Such operations are supported by the `reduction` clause.

- If multiple threads manipulate different parts of a large data structure, the programmer should explore ways of breaking it into smaller data structures and making them private to the thread manipulating them.

- After all the above techniques have been explored and exhausted, remaining data items may be shared among various threads using the clause `shared`.

In addition to `private`, `shared`, `firstprivate`, and `lastprivate`, OpenMP supports one additional data class called `threadprivate`.

The `threadprivate` and `copyin` Directives Often, it is useful to make a set of objects locally available to a thread in such a way that these objects persist through parallel and serial blocks provided the number of threads remains the same. In contrast to `private` variables, these variables are useful for maintaining persistent objects across parallel regions, which would otherwise have to be copied into the master thread's data space and reinitialized at the next parallel block. This class of variables is supported in OpenMP using the `threadprivate` directive. The syntax of the directive is as follows:

```
1   #pragma omp threadprivate(variable_list)
```

This directive implies that all variables in `variable_list` are local to each thread and are initialized once before they are accessed in a parallel region. Furthermore, these variables persist across different parallel regions provided dynamic adjustment of the number of threads is disabled and the number of threads is the same.

Similar to `firstprivate`, OpenMP provides a mechanism for assigning the same value to `threadprivate` variables across all threads in a parallel region. The syntax of the clause, which can be used with `parallel` directives, is `copyin(variable_list)`.

7.10.5 OpenMP Library Functions

In addition to directives, OpenMP also supports a number of functions that allow a programmer to control the execution of threaded programs. As we shall notice, these functions are similar to corresponding Pthreads functions; however, they are generally at a higher level of abstraction, making them easier to use.

Controlling Number of Threads and Processors

The following OpenMP functions relate to the concurrency and number of processors used by a threaded program:

```
1   #include <omp.h>
2
3   void omp_set_num_threads (int num_threads);
```

```
4   int omp_get_num_threads ();
5   int omp_get_max_threads ();
6   int omp_get_thread_num ();
7   int omp_get_num_procs ();
8   int omp_in_parallel();
```

The function `omp_set_num_threads` sets the default number of threads that will be created on encountering the next `parallel` directive provided the `num_threads` clause is not used in the `parallel` directive. This function must be called outsid the scope of a parallel region and dynamic adjustment of threads must be enabled (using either the `OMP_DYNAMIC` environment variable discussed in Section 7.10.6 or the `omp_set_dynamic` library function).

The `omp_get_num_threads` function returns the number of threads participating in a team. It binds to the closest parallel directive and in the absence of a parallel directive, returns 1 (for master thread). The `omp_get_max_threads` function returns the maximum number of threads that could possibly be created by a `parallel` directive encountered, which does not have a `num_threads` clause. The `omp_get_thread_num` returns a unique thread i.d. for each thread in a team. This integer lies between 0 (for the master thread) and `omp get_num_threads() -1`. The `omp_get_num_procs` function returns the number of processors that are available to execute the threaded program at that point. Finally, the function `omp_in_parallel` returns a non-zero value if called from within the scope of a parallel region, and zero otherwise.

Controlling and Monitoring Thread Creation

The following OpenMP functions allow a programmer to set and monitor thread creation:

```
1   #include <omp.h>
2
3   void omp_set_dynamic (int dynamic_threads);
4   int omp_get_dynamic ();
5   void omp_set_nested (int nested);
6   int omp_get_nested ();
```

The `omp_set_dynamic` function allows the programmer to dynamically alter the number of threads created on encountering a parallel region. If the value `dynamic_threads` evaluates to zero, dynamic adjustment is disabled, otherwise it is enabled. The function must be called outside the scope of a parallel region. The corresponding state, i.e., whether dynamic adjustment is enabled or disabled, can be queried using the function `omp_get_dynamic`, which returns a non-zero value if dynamic adjustment is enabled, and zero otherwise.

The `omp_set_nested` enables nested parallelism if the value of its argument, `nested`, is non-zero, and disables it otherwise. When nested parallelism is disabled, any nested parallel regions subsequently encountered are serialized. The state of nested parallelism can be queried using the `omp_get_nested` function, which returns a non-zero value if nested parallelism is enabled, and zero otherwise.

Mutual Exclusion

While OpenMP provides support for critical sections and atomic updates, there are situations where it is more convenient to use an explicit lock. For such programs,

OpenMP provides functions for initializing, locking, unlocking, and discarding locks. The lock data structure in OpenMP is of type `omp_lock_t`. The following functions are defined:

```
1   #include <omp.h>
2
3   void omp_init_lock (omp_lock_t *lock);
4   void omp_destroy_lock (omp_lock_t *lock);
5   void omp_set_lock (omp_lock_t *lock);
6   void omp_unset_lock (omp_lock_t *lock);
7   int omp_test_lock (omp_lock_t *lock);
```

Before a lock can be used, it must be initialized. This is done using the `omp_init_lock` function. When a lock is no longer needed, it must be discarded using the function `omp_destroy_lock`. It is illegal to initialize a previously initialized lock and destroy an uninitialized lock. Once a lock has been initialized, it can be locked and unlocked using the functions `omp_set_lock` and `omp_unset_lock`. On locking a previously unlocked lock, a thread gets exclusive access to the lock. All other threads must wait on this lock when they attempt an `omp_set_lock`. Only a thread owning a lock can unlock it. The result of a thread attempting to unlock a lock owned by another thread is undefined. Both of these operations are illegal prior to initialization or after the destruction of a lock. The function `omp_test_lock` can be used to attempt to set a lock. If the function returns a non-zero value, the lock has been successfully set, otherwise the lock is currently owned by another thread.

Similar to recursive mutexes in Pthreads, OpenMP also supports nestable locks that can be locked multiple times by the same thread. The lock object in this case is `omp_nest_lock_t` and the corresponding functions for handling a nested lock are:

```
1   #include <omp.h>
2
3   void omp_init_nest_lock (omp_nest_lock_t *lock);
4   void omp_destroy_nest_lock (omp_nest_lock_t *lock);
5   void omp_set_nest_lock (omp_nest_lock_t *lock);
6   void omp_unset_nest_lock (omp_nest_lock_t *lock);
7   int omp_test_nest_lock (omp_nest_lock_t *lock);
```

The semantics of these functions are similar to corresponding functions for simple locks. Notice that all of these functions have directly corresponding mutex calls in Pthreads.

7.10.6 Environment Variables in OpenMP

OpenMP provides additional environment variables that help control execution of parallel programs. These environment variables include the following.

`OMP_NUM_THREADS` This environment variable specifies the default number of threads created upon entering a `parallel` region. The number of threads can be changed using either the `omp_set_num_threads` function or the `num_threads` clause in the `parallel` directive. Note that the number of threads can be changed dynamically only if the variable `OMP_SET_DYNAMIC` is set to `TRUE` or if the function `omp_set_dynamic` has been called with a non-zero argument. For example, the following command, when typed into `csh` prior to execution of the program, sets the default number of threads to 8.

```
1   setenv OMP_NUM_THREADS 8
```

OMP_DYNAMIC This variable, when set to TRUE, allows the number of threads to be controlled at runtime using the omp_set_num_threads function or the num_threads clause. Dynamic control of number of threads can be disabled by calling the omp_set_dynamic function with a zero argument.

OMP_NESTED This variable, when set to TRUE, enables nested parallelism, unless it is disabled by calling the omp_set_nested function with a zero argument.

OMP_SCHEDULE This environment variable controls the assignment of iteration spaces associated with for directives that use the runtime scheduling class. The variable can take values static, dynamic, and guided along with optional chunk size. For example, the following assignment:

```
1   setenv OMP_SCHEDULE "static,4"
```

specifies that by default, all for directives use static scheduling with a chunk size of 4. Other examples of assignments include:

```
1   setenv OMP_SCHEDULE "dynamic"
2   setenv OMP_SCHEDULE "guided"
```

In each of these cases, a default chunk size of 1 is used.

7.10.7 Explicit Threads versus OpenMP Based Programming

OpenMP provides a layer on top of native threads to facilitate a variety of thread-related tasks. Using directives provided by OpenMP, a programmer is rid of the tasks of initializing attributes objects, setting up arguments to threads, partitioning iteration spaces, etc. This convenience is especially useful when the underlying problem has a static and/or regular task graph. The overheads associated with automated generation of threaded code from directives have been shown to be minimal in the context of a variety of applications.

However, there are some drawbacks to using directives as well. An artifact of explicit threading is that data exchange is more apparent. This helps in alleviating some of the overheads from data movement, false sharing, and contention. Explicit threading also provides a richer API in the form of condition waits, locks of different types, and increased flexibility for building composite synchronization operations as illustrated in Section 7.8. Finally, since explicit threading is used more widely than OpenMP, tools and support for Pthreads programs is easier to find.

A programmer must weigh all these considerations before deciding on an API for programming.

CHAPTER

17

Shared-Memory Programming

Not what we give, but what we share—
For the gift without the giver is bare;
Who gives himself with his alms feeds three—
Himself, his hungering neighbor, and me.
James Russell Lowell, ***The Vision of Sir Launfal***

17.1 INTRODUCTION

In the 1980s commercial multiprocessors with a modest number of CPUs cost hundreds of thousands of dollars. Today, multiprocessors with dozens of processors are still quite expensive, but small systems are readily available for a low price. Dell, Gateway, and other companies sell dual-CPU multiprocessors for less than $5,000, and you can purchase a quad-processor system for less than $20,000.

It is possible to write parallel programs for multiprocessors using MPI, but you can often achieve better performance by using a programming language tailored for a shared-memory environment. Recently, OpenMP has emerged as a shared-memory standard. OpenMP is an application programming interface (API) for parallel programming on multiprocessors. It consists of a set of compiler directives and a library of support functions. OpenMP works in conjunction with standard Fortran, C, or C++.

This chapter introduces shared-memory parallel programming using OpenMP. You can use it in two different ways. Perhaps the only parallel computer you have access to is a multiprocessor. In that case, you may prefer to write programs using OpenMP rather than MPI.

On the other hand, you may have access to a multicomputer consisting of many nodes, each of which is a multiprocessor. This is a popular way to build large multicomputers with hundreds or thousands of processors. Consider

these examples (circa 2002):

- IBM's RS/6000 SP system contains up to 512 nodes. Each node can have up to 16 CPUs in it.
- Fujitsu's AP3000 Series supercomputer contains up to 1024 nodes, and each node consists of one or two UltraSPARC processors.
- Dell's High Performance Computing Cluster has up to 64 nodes. Each node is a multiprocessor with two Pentium III CPUs.

In this chapter you'll see how the shared-memory programming model is different from the message-passing model, and you'll learn enough OpenMP compiler directives and functions to be able to parallelize a wide variety of C code segments.

This chapter introduces a powerful set of OpenMP compiler directives:

- `parallel`, which precedes a block of code to be executed in parallel by multiple threads
- `for`, which precedes a `for` loop with independent iterations that may be divided among threads executing in parallel
- `parallel for`, a combination of the `parallel` and `for` directives
- `sections`, which precedes a series of blocks that may be executed in parallel
- `parallel sections`, a combination of the `parallel` and `sections` directives
- `critical`, which precedes a critical section
- `single`, which precedes a code block to be executed by a single thread

You'll also encounter four important OpenMP functions:

- `omp_get_num_procs`, which returns the number of CPUs in the multiprocessor on which this thread is executing
- `omp_get_num_threads`, which returns the number of threads active in the current parallel region
- `omp_get_thread_num`, which returns the thread identification number
- `omp_set_num_threads`, which allows you to fix the number of threads executing the parallel sections of code

17.2 THE SHARED-MEMORY MODEL

The shared-memory model (Figure 17.1) is an abstraction of the generic centralized multiprocessor described in Section 2.4. The underlying hardware is assumed to be a collection of processors, each with access to the same shared memory. Because they have access to the same memory locations, processors can interact and synchronize with each other through shared variables.

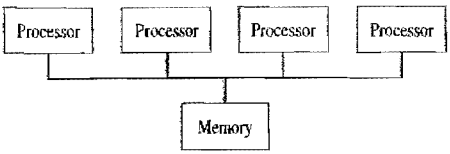


Figure 17.1 The shared-memory model of parallel computation. Processors synchronize and communicate with each other through shared variables.

The standard view of parallelism in a shared-memory program is **fork/join parallelism.** When the program begins execution, only a single thread, called the **master thread,** is active (Figure 17.2). The master thread executes the sequential portions of the algorithm. At those points where parallel operations are required, the master thread forks (creates or awakens) additional threads. The master thread and the created threads work concurrently through the parallel section. At the end of the parallel code the created threads die or are suspended, and the flow of control returns to the single master thread. This is called a join.

A key difference, then, between the shared-memory model and the message-passing model is that in the message-passing model all processes typically remain active throughout the execution of the program, whereas in the shared-memory model the number of active threads is one at the program's start and finish and may change dynamically throughout the execution of the program.

You can view a sequential program as a special case of a shared-memory parallel program: it is simply one with no fork/joins in it. Parallel shared-memory programs range from those with only a single fork/join around a single loop to those in which most of the code segments are executed in parallel. Hence the shared-memory model supports **incremental parallelization,** the process of transforming a sequential program into a parallel program one block of code at a time.

The ability of the shared-memory model to support incremental parallelization is one of its greatest advantages over the message-passing model. It allows you to profile the execution of a sequential program, sort the program blocks according to how much time they consume, consider each block in turn beginning with the most time-consuming, parallelize each block amenable to parallel execution, and stop when the effort required to achieve further performance improvements is not warranted.

Consider, in contrast, message-passing programs. They have no shared memory to hold variables, and the parallel processes are active throughout the execution of the program. Transforming a sequential program into a parallel program is not incremental at all—the chasm must be crossed with one giant leap, rather than many small steps.

In this chapter you'll encounter increasingly complicated blocks of sequential code and learn how to transform them into parallel code sections.

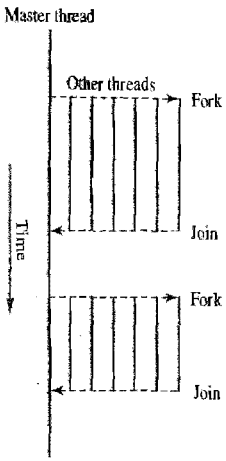


Figure 17.2 The shared-memory model is characterized by fork/join parallelism, in which parallelism comes and goes. At the beginning of execution only a single thread, called the master thread, is active. The master thread executes the serial portions of the program. It forks additional threads to help it execute parallel portions of the program. These threads are deactivated when serial execution resumes.

17.3 PARALLEL `for` LOOPS

Inherently parallel operations are often expressed in C programs as `for` loops. OpenMP makes it easy to indicate when the iterations of a `for` loop may be executed in parallel. For example, consider the following loop, which accounts for a large proportion of the execution time in our MPI implementation of the Sieve of Eratosthenes:

```
for (i = first; i < size; i += prime) marked[i] = 1;
```

Clearly there is no dependence between one iteration of the loop and another. How do we convert it into a parallel loop? In OpenMP we simply indicate to

the compiler that the iterations of a `for` loop may be executed in parallel; the compiler takes care of generating the code that forks/joins threads and **schedules** the iterations, that is, allocates iterations to threads.

17.3.1 `parallel for` Pragma

A compiler directive in C or C++ is called a **pragma.** The word *pragma* is short for "pragmatic information." A pragma is a way to communicate information to the compiler. The information is nonessential in the sense that the compiler may ignore the information and still produce a correct object program. However, the information provided by the pragma can help the compiler optimize the program.

Like other lines that provide information to the preprocessor, a pragma begins with the # character. A pragma in C or C++ has this syntax:

```
#pragma omp <rest of pragma>
```

The first pragma we are going to consider is the `parallel for` pragma. The simplest form of the `parallel for` pragma is:

```
#pragma omp parallel for
```

Putting this line immediately before the `for` loop instructs the compiler to try to parallelize the loop:

```
#pragma omp parallel for
  for (i = first; i < size; i += prime) marked[i] = 1;
```

In order for the compiler to successfully transform the sequential loop into a parallel loop, it must be able to verify that the run-time system will have the information it needs to determine the number of loop iterations when it evaluates the control clause. For this reason the control clause of the `for` loop must have **canonical shape,** as illustrated in Figure 17.3. In addition, the `for` loop must not contain statements that allow the loop to be exited prematurely. Examples include the `break` statement, `return` statement, `exit` statement, and `goto` statements

```
for (index = start; index { <, <=, >=, > } end; { index++, ++index, index--, --index, index += inc, index -= inc, index = index + inc, index = inc + index, index = index - inc } )
```

Figure 17.3 In order to be made parallel, the control clause of a `for` loop must have canonical shape. This figure shows the legal variants. The identifiers *start, end,* and *inc* may be expressions.

to labels outside the loop. The `continue` statement is allowed, however, because its execution does not affect the number of loop iterations.

Our example `for` loop

```
for (i = first; i < size; i += prime) marked[i] = 1;
```

meets these criteria: the control clause has canonical shape, and there are no premature exits in the body of the loop. Hence the compiler can generate code that allows its iterations to execute in parallel.

During parallel execution of the `for` loop, the master thread creates additional threads, and all threads work together to cover the iterations of the loop. Every thread has its own **execution context:** an address space containing all of the variables the thread may access. The execution context includes static variables, dynamically allocated data structures in the heap, and variables on the run-time stack.

The execution context includes its own additional run-time stack, where the frames for functions it invokes are kept. Other variables may either be shared or private. A **shared variable** has the same address in the execution context of every thread. All threads have access to shared variables. A **private variable** has a different address in the execution context of every thread. A thread can access its own private variables, but cannot access the private variable of another thread.

In the case of the `parallel for` pragma, variables are by default shared, with the exception that the loop index variable is private.

Figure 17.4 illustrates shared and private variables. In this example the iterations of the `for` loop are being divided among two threads. The loop index `i` is a private variable—each thread has its own copy. The remaining variables `b` and `ptr`, as well as data allocated on the heap, are shared.

How does the run-time system know how many threads to create? The value of an environment variable called `OMP_NUM_THREADS` provides a default number of threads for parallel sections of code. In Unix you can use the `printenv` command to inspect the value of this variable and the `setenv` command to modify its value.

```
int main (int argc, char* argv[])
{
  int b[3];
  char* cptr ;
  int i;

  cptr = malloc (1);
#pragma omp parallel for
  for (i=0; i<3; i++)
    b[i]=i;
```

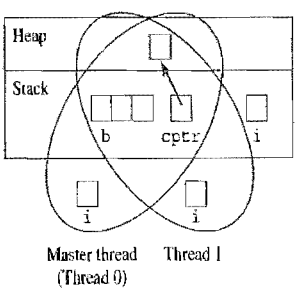


Figure 17.4 During parallel execution of the `for` loop, index `i` is a private variable, while `b`, `cptr`, and heap data are shared.

Another strategy is to set the number of threads equal to the number of multiprocessor CPUs. Let's explore the OpenMP functions that enable us to do this.

17.3.2 Function `omp_get_num_procs`

Function `omp_get_num_procs` returns the number of physical processors available for use by the parallel program. Here is the function header:

```
int omp_get_num_procs (void)
```

The integer returned by this function may be less than the total number of physical processors in the multiprocessor, depending on how the run-time system gives processes access to processors.

17.3.3 Function `omp_set_num_threads`

Function `omp_set_num_threads` uses the parameter value to set the number of threads to be active in parallel sections of code. It has this function header:

```
void omp_set_num_threads (int t)
```

Since this function may be called at multiple points in a program, you have the ability to tailor the level of parallelism to the grain size or other characteristics of the code block.

Setting the number of threads equal to the number of available CPUs is straightforward:

```
int t;
...
t = omp_get_num_procs();
omp_set_num_threads(t);
```

17.4 DECLARING PRIVATE VARIABLES

For our second example, let's look at slightly more complicated loop structure. Here is the computational heart of our MPI implementation of Floyd's algorithm:

```
for (i = 0; i < BLOCK_SIZE(id,p,n); i++)
   for (j = 0; j < n; j++)
      a[i][j] = MIN(a[i][j], a[i][k] + tmp[j]);
```

In our earlier analysis of this algorithm, we determined that either loop could be executed in parallel. Which one should we choose? If we parallelize the inner loop, then the program will fork and join threads for every iteration of the outer loop. The fork/join overhead may very well be greater than the time saved by dividing the execution of the n iterations of the inner loop among multiple threads. On the other hand, if we parallelize the outer loop, the program only incurs the fork/join overhead once.

Grain size is the number of computations performed between communication or synchronization steps. In general, increasing grain size improves the performance of a parallel program. Making the outer loop parallel results in larger grain size. It is the option we choose.

It's easy enough to direct the compiler to execute the iterations of the loop indexed by `i` in parallel. However, we need to pay attention to the variables accessed by the threads. By default, all variables are shared except loop index `i`. That makes it easy for threads to communicate with each other, but it can also cause problems.

Consider what happens when multiple threads try to execute different iterations of the `i` loop in parallel. We want every thread to work through `n` values of `j` for each iteration of the `i` loop. However, all of the threads try to initialize and increment the same shared variable `j`—meaning that there is a good chance threads will not execute all `n` iterations.

The solution is clear—we need to make `j` a private variable, too.

17.4.1 `private` Clause

A clause is an optional, additional component to a pragma. The `private` clause directs the compiler to make one or more variables private. It has this syntax:

`private (`*<variable list>*`)`

The directive tells the compiler to allocate a private copy of the variable for each thread executing the block of code the pragma precedes. In our case, we are making a `for` loop parallel. The private copies of variable `j` will be accessible only inside the `for` loop. The values are undefined on loop entry and exit.

Using the `private` clause, a correct OpenMP implementation of the doubly nested loops is

```
#pragma omp parallel for private(j)
   for (i = 0; i < BLOCK_SIZE(id,p,n); i++)
      for (j = 0; j < n; j++)
         a[i][j] = MIN(a[i][j], a[i][k] + tmp[j]);
```

Even if `j` had a previously assigned value before entering the parallel `for` loop, none of the threads can access that value. Similarly, whatever values the threads assign to `j` during execution of the parallel `for` loop, the value of the shared `j` will not be affected. Put another way, by default the value of a private variable is undefined when the parallel construct is entered, and the value is also undefined when the construct is exited.

The default condition of private variables (undefined at loop entry and exit) reduces execution time by eliminating unnecessary copying between shared variables and their private variable counterparts.

17.4.2 `firstprivate` Clause

Sometimes we want a private variable to inherit the value of the shared variable. Consider, for example, the following code segment:

```
x[0] = complex_function();
for (i = 0; i < n; i++) {
   for (j = 1 ; j < 4; j++)
      x[j] = g(i, x[j-1]);
   answer[i] = x[1] - x[3];
}
```

Assuming function g has no side effects, we may execute every iteration of the outer loop in parallel, as long as we make x a private variable. However, `x[0]` is initialized before the outer `for` loop and referenced in the first iteration of the inner loop. It is impractical to move the initialization of `x[0]` inside the outer `for` loop, because it is too time-consuming. Instead, we want each thread's private copy of array element `x[0]` to inherit the value the shared variable was assigned in the master thread.

The `firstprivate` clause, with syntax

`firstprivate (`*<variable list>*`)`

does just that. It directs the compiler to create private variables having initial values identical to the value of the variable controlled by the master thread as the loop is entered.

Here is the correct way to code the parallel loop:

```
x[0] = complex_function();
#pragma omp parallel for private(j) firstprivate(x)
for (i = 0; i < n; i++) {
   for (j = 1 ; j < 4; j++)
      x[j] = g(i, x[j-1]);
   answer[i] = x[1] - x[3];
}
```

Note that the values of the variables in the `firstprivate` list are initialized once per thread, not once per iteration. If a thread executes multiple iterations of the parallel loop and modifies the value of one of these variables in an iteration, then subsequent iterations referencing the variable will get the modified value, not the original value.

17.4.3 `lastprivate` Clause

The **sequentially last iteration** of a loop is the iteration that occurs last when the loop is executed sequentially. The `lastprivate` clause directs the compiler to generate code at the end of the parallel `for` loop that copies back to the master

thread's copy of a variable the private copy of the variable from the thread that executed the sequentially last iteration of the loop.

For example, suppose we were parallelizing the following piece of code:

```
for (i = 0; i < n; i++) {
   x[0] = 1.0;
   for (j = 1 ; j < 4; j++)
      x[j] = x[j-1] * (i+1);
   sum_of_powers[i] = x[0] + x[1] + x[2] + x[3];
}
n_cubed = x[3];
```

In the sequentially last iteration of the loop, `x[3]` gets assigned the value n^3. In order to have this value accessible outside the parallel `for` loop, we must declare `x` to be a `lastprivate` variable. Here is the correct parallel version of the loop:

```
#pragma omp parallel for private(j) lastprivate(x)
for (i = 0; i < n; i++) {
   x[0] = 1.0;
   for (j = 1 ; j < 4; j++)
      x[j] = x[j-1] * (i+1);
   sum_of_powers[i] = x[0] + x[1] + x[2] + x[3];
}
n_cubed = x[3];
```

A `parallel for` pragma may contain both `firstprivate` and `lastprivate` clauses. If the same pragma has both of these clauses, the clauses may have none, some, or all of the variables in common.

17.5 CRITICAL SECTIONS

Let's consider part of a C program that estimates the value of π using a form of numerical integration called the rectangle rule:

```
double area, pi, x;
int i, n;
...
area = 0.0;
for (i = 0; i < n; i++) {
   x = (i+0.5)/n;
   area += 4.0/(1.0 + x*x);
}
pi = area / n;
```

Unlike the `for` loops we have already considered, the iterations of this loop are not independent of each other. Each iteration of the loop reads and updates the value of `area`. If we simply parallelize the loop:

```
   double area, pi, x;
   int i, n;
   ...
   area = 0.0;
#pragma omp parallel for private(x)
   for (i = 0; i < n; i++) {
      x = (i+0.5)/n;
      area += 4.0/(1.0 + x*x);   /* Race condition! */
   }
   pi = area / n;
```

we may not end up with the correct answer, because the execution of the assignment statement is not an atomic (indivisible) operation. This sets up a **race condition,** in which the computation exhibits nondeterministic behavior when performed by multiple threads accessing a shared variable.

See Figure 17.5. Suppose thread A and thread B are concurrently executing different iterations of the loop. Thread A reads the current value of `area` and computes the sum

```
area + 4.0/(1.0 + x*x)
```

Before it can write the value of the sum back to `area`, thread B reads the current value of `area`. Thread A updates the value of `area` with the sum. Thread B computes its sum and writes back the value. Now the value of `area` is incorrect.

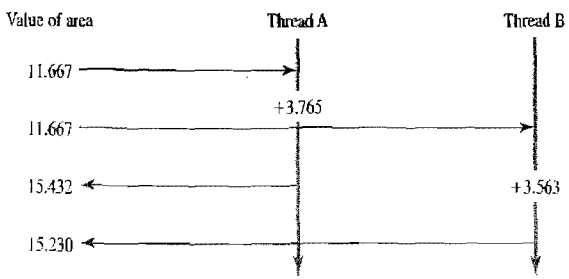


Figure 17.5 Example of a race condition. Each thread is adding a value to `area`. However, Thread B retrieves the original value of `area` before Thread A can write the new value. Hence the final value of `area` is incorrect. If Thread B had read the value of `area` after Thread A had updated it, then the final value of `area` would have been correct. In short, the absence of a critical section can lead to nondeterministic execution.

The assignment statement that reads and updates `area` must be put in a **critical section**—a portion of code that only one thread at a time may execute.

17.5.1 `critical` Pragma

We can denote a critical section in OpenMP by putting the pragma

```
#pragma omp critical
```

in front of a block of C code. (A single statement is a trivial example of a code block.) This pragma directs the compiler to enforce mutual exclusion among the threads trying to execute the block of code.

After adding the critical pragma, our code looks like this:

```
   double area, pi, x;
   int i, n;
   ...
   area = 0.0;
#pragma omp parallel for private(x)
   for (i = 0; i < n; i++) {
      x = (i+0.5)/n;
#pragma omp critical
      area += 4.0/(1.0 + x*x);
   }
   pi = area / n;
```

At this point our C/OpenMP code segment will produce the correct result. The iterations of the `for` loop are divided among the threads, and only one thread at a time may execute the assignment statement that updates the value of `area`. However, this code segment will exhibit poor speedup. Since it admits only one thread at a time, the critical section is a piece of sequential code inside the `for` loop. The time to execute this statement is nontrivial. Hence by Amdahl's Law we know the critical section will put a low ceiling on the speedup achievable by parallelizing the `for` loop.

Of course, what we are really trying to do is perform a sum-reduction of `n` values. In the next section we'll learn an efficient way to code a reduction.

17.6 REDUCTIONS

Reductions are so common that OpenMP allows us to add a reduction clause to our `parallel for` pragma. All we have to do is specify the reduction operation and the **reduction variable**, and OpenMP will take care of the details, such as storing partial sums in private variables and then adding the partial sums to the shared variable after the loop.

The reduction clause has this syntax:

`reduction(<op>:<variable>)`

where *<op>* is one of the reduction operators shown in Table 17.1 and *<variable>* is the name of the shared variable that will end up with the result of the reduction.

Here is an implementation of the π-finding code with the reduction clause replacing the critical section:

```
   double area, pi, x;
   int i, n;
   ...
   area = 0.0;
#pragma omp parallel for private(x) reduction(+:area)
   for (i = 0; i < n; i++) {
      x = (i+0.5)/n;
      area += 4.0/(1.0 + x*x);
   }
   pi = area / n;
```

Table 17.2 compares our two implementations of the rectangle rule to compute π. We set $n = 100{,}000$ and execute the programs on a Sun Enterprise Server 4000. The implementation that uses the `reduction` clause is clearly superior to the one using the `critical` pragma. It is faster when only a single thread is active, and the execution time improves when additional threads are added.

Table 17.1 OpenMP reduction operators for C and C++.

Operator	Meaning	Allowable types	Initial value
+	Sum	float, int	0
*	Product	float, int	1
&	Bitwise and	int	all bits 1
|	Bitwise or	int	0
^	Bitwise exclusive or	int	0
&&	Logical and	int	1
||	Logical or	int	0

Table 17.2 Execution times on a Sun Enterprise Server 4000 of two programs that compute π using the rectangle rule.

	Execution time of program (sec)	
Threads	Using `critical` pragma	Using `reduction` clause
1	0.0780	0.0273
2	0.1510	0.0146
3	0.3400	0.0105
4	0.3608	0.0086
5	0.4710	0.0076

17.7 PERFORMANCE IMPROVEMENTS

Sometimes transforming a sequential `for` loop into a parallel `for` loop can actually increase a program's execution time. In this section we'll look at three ways of improving the performance of parallel loops.

17.7.1 Inverting Loops

Consider the following code segment:

```
for (i = 1; i < m; i++)
   for (j = 0; j < n; j++)
      a[i][j] = 2 * a[i-1][j];
```

We can draw a data dependence diagram to help us understand the data dependences in this code. The diagram appears in Figure 17.6. We see that two rows may not be updated simultaneously, because there are data dependences between rows. However, the columns may be updated simultaneously. This means the loop indexed by `j` may be executed in parallel, but not the loop indexed by `i`.

If we insert a `parallel for` pragma before the inner loop, the resulting parallel program will execute correctly, but it may not exhibit good performance, because it will require `m-1` fork/join steps, one per iteration of the outer loop.

However, if we invert the loops:

```
#pragma parallel for private(i)
for (j = 0; j < n; j++)
   for (i = 1; i < m; i++)
      a[i][j] = 2 * a[i-1][j];
```

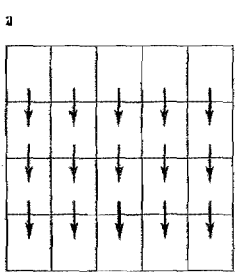


Figure 17.6 Data dependence diagram for a particular pair of nested loops shows that while columns may be updated simultaneously, rows cannot.

only a single fork/join step is required (surrounding the outer loop). The data dependences have not changed; the iterations of the loop indexed by `j` are still independent of each other. In this respect we have definitely improved the code.

However, we must always be cognizant of how code transformations affect the cache hit rate. In this case, each thread is now working through columns of `a`, rather than rows. Since C matrices are stored in row-major order, inverting loops may lower the cache hit rate, depending upon `m`, `n`, the number of active threads, and the architecture of the underlying system.

17.7.2 Conditionally Executing Loops

If a loop does not have enough iterations, the time spent forking and joining threads may exceed the time saved by dividing the loop iterations among multiple threads. Consider, for example, the parallel implementation of the rectangle rule we examined earlier:

```
   area = 0.0;
#pragma omp parallel for private(x) reduction (+:area)
   for (i = 0; i < n; i++) {
      x = (i + 0.5)/n;
      area += 4.0 / (1.0 + x * x);
   }
   pi = area / n;
```

Table 17.3 reveals the average execution time of this program segment on a Sun Enterprise Server 4000, for various values of `n` and various numbers of threads. As you can see, when `n` is 100, the sequential execution time is so small that adding threads only increases overall execution time. When `n` is 100,000, the parallel program executing on four threads achieves a speedup of 3.16 over the sequential program.

The `if` clause gives us the ability to direct the compiler to insert code that determines at run-time whether the loop should be executed in parallel or

Table 17.3 Execution time on a Sun Enterprise Server 4000 of a parallel C program that computes π using the rectangle rule, as a function of number of rectangles and number of threads.

	Execution time (msec)	
Threads	$n = 100$	$n = 100{,}000$
1	0.964	27.288
2	1.436	14.598
3	1.732	10.506
4	1.990	8.648

sequentially. The clause has this syntax:

`if (`*<scalar expression>*`)`

If the scalar expression evaluates to true, the loop will be executed in parallel. Otherwise, it will be executed serially.

For example, here is how we could add an `if` clause to the `parallel for` pragma in the parallel program computing π using the rectangle rule:

```
#pragma omp parallel for private(x) reduction(+:area) if(n > 5000)
   for (i = 0; i < n; i++) {
   ...
```

In this case loop iterations will be divided among multiple threads only if $n > 5{,}000$.

17.7.3 Scheduling Loops

In some loops the time needed to execute different loop iterations varies considerably. For example, consider the following doubly nested loop that initializes an upper triangular matrix:

```
for (i = 0; i < n; i++)
   for (j = i; j < n; j++)
      a[i][j] = alpha_omega(i,j);
```

Assuming there are no data dependences among iterations, we would prefer to execute the outermost loop in parallel in order to minimize fork/join overhead. If every call to function `alpha_omega` takes the same amount of time, then the first iteration of the outermost loop (when `i` equals 0) requires `n` times more work than the last iteration (when `i` equals `n-1`). Inverting the two loops will not remedy the imbalance.

Suppose these n iterations are being executed on t threads. If each thread is assigned a contiguous block of either $\lceil n/t \rceil$ or $\lfloor n/t \rfloor$ threads, the parallel loop execution will have poor efficiency, because some threads will complete their share of the iterations much faster than others.

The `schedule` clause allows us to specify how the iterations of a loop should be scheduled, that is, allocated to threads. In a **static schedule,** all iterations are allocated to threads before they execute any loop iterations. In a **dynamic schedule,** only some of the iterations are allocated to threads at the beginning of the loop's execution. Threads that complete their iterations are then eligible to get additional work. The allocation process continues until all of the iterations have been distributed to threads. Static schedules have low overhead but may exhibit high load imbalance. Dynamic schedules have higher overhead but can reduce load imbalance.

In both static and dynamic schedules, contiguous ranges of iterations called **chunks** are assigned to threads. Increasing the chunk size can reduce overhead

and increase the cache hit rate. Reducing the chunk size can allow finer balancing of workloads.

The schedule clause has this syntax:

```
schedule(<type> [, <chunk>])
```

In other words, the schedule type is required, but the chunk size is optional. With these two parameters it's easy to describe a wide variety of schedules:

- `schedule(static)`: A static allocation of about `n/t` contiguous iterations to each thread.
- `schedule(static,C)`: An interleaved allocation of chunks to tasks. Each chunk contains C contiguous iterations.
- `schedule(dynamic)`: Iterations are dynamically allocated, one at a time, to threads.
- `schedule(dynamic,C)`: A dynamic allocation of C iterations at a time to the tasks.
- `schedule(guided,C)`: A dynamic allocation of iterations to tasks using the guided self-scheduling heuristic. **Guided self-scheduling** begins by allocating a large chunk size to each task and responds to further requests for chunks by allocating chunks of decreasing size. The size of the chunks decreases exponentially to a minimum chunk size of C.
- `schedule(guided)`: Guided self-scheduling with a minimum chunk size of 1.
- `schedule(runtime)`: The schedule type is chosen at run-time based on the value of the environment variable `OMP_SCHEDULE`. For example, the Unix command

  ```
  setenv OMP_SCHEDULE "static,1"
  ```

  would set the run-time schedule to be an interleaved allocation.

When the `schedule` clause is not included in the `parallel for` pragma, most run-time systems default to a simple static scheduling of consecutive loop iterations to tasks.

Going back to our original example, the run-time of any particular iteration of the outermost `for` loop is predictable. An interleaved allocation of loop iterations balances the workload of the threads:

```
#pragma omp parallel for private(j) schedule(static,1)
for (i = 0; i < n; i++)
   for (j = i; j < n; j++)
      a[i][j] = alpha_omega(i,j);
```

Increasing the chunk size from 1 could improve the cache hit rate at the expense of increasing the load imbalance. The best value for the chunk size is system-dependent.

17.8 MORE GENERAL DATA PARALLELISM

To this point we have focused on the parallelization of simple `for` loops. They are perhaps the most common opportunity for parallelism, particularly in programs that have already been written in MPL However, we should not ignore other opportunities for concurrency. In this section we look at two examples of data parallelism outside simple `for` loops.

First let's consider an algorithm to process a linked list of tasks. We considered a similar algorithm when we designed a solution to the document classification problem in Chapter 9. In that design, we assumed a message-passing model. Because that model has no shared memory, we gave a single process, which we called the manager, responsibility for maintaining the entire list of tasks. Worker tasks sent messages to the manager when they were ready to process another task.

In contrast, the shared-memory model allows every thread to access the same "to-do" list, so there is no need for a separate manager thread.

The following code segments are part of a program that processes work stored in a singly linked to-do list (see Figure 17.7):

```
int main (int argc, char argv[])
{
   struct job_struct job_ptr;
   struct task_struct task_ptr;

   ...
   task_ptr = get_next_task (&job_ptr);
   while (task_ptr != NULL) {
      complete_task (task_ptr);
      task_ptr = get_next_task (&job_ptr);
   }
   ...
}

char get_next_task(struct job_struct job_ptr) {
   struct task_struct answer;
   if (job_ptr == NULL) answer = NULL;
   else {
      answer = (job_ptr)->task;
      job_ptr = (job_ptr)->next;
   }
   return answer;
}
```

How would we like this algorithm to execute in parallel? We want every thread to do the same thing: repeatedly take the next task from the list and complete it, until there are no more tasks to do. We need to ensure that no two threads take the same task from the list. In other words, it is important to execute function `get_next_task` atomically.

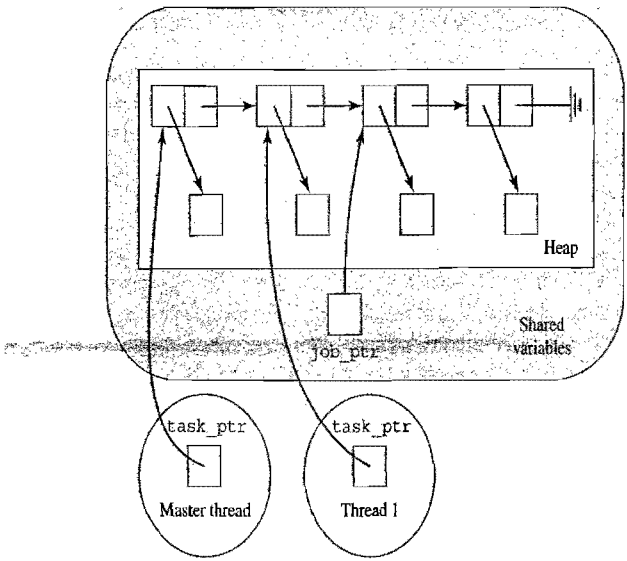


Figure 17.7 Two threads work their way through a singly linked "to do" list. Variable `job_ptr` must be shared, while `task_ptr` must be a private variable.

17.8.1 `parallel` Pragma

The parallel pragma precedes a block of code that should be executed by all of the threads. It has this syntax:

```
#pragma omp parallel
```

If the code we want executed in parallel is not a simple statement (such as an assignment statement, `if` statement, or `for` loop) we can use curly braces to create a block of code from a statement group.

Note that unlike the `parallel for` pragma, which divided the iterations of the `for` loop among the active threads, the execution of the code block after the parallel program is replicated among the threads. Our section of function `main` now looks like this:

```
int main (int argc, char argv[])
{
   struct job_struct job_ptr;
   struct task_struct task_ptr;

#pragma omp parallel private (task_ptr)
   {
      task_ptr = get_next_task (&job_ptr);
```

```
      while (task_ptr != NULL) {
         complete_task (task_ptr);
         task_ptr = get_next_task (&job_ptr);
      }
   }
}
```

Now we need to ensure function `get_next_task` executes atomically. Otherwise, allowing two threads to execute function `get_next_task` simultaneously may result in more than one thread returning from the function with the same value of `task_ptr`.

We use the `critical` pragma to ensure mutually exclusive execution of this critical section of code. Here is the rewritten function `get_next_task`:

```
char get_next_task(struct job_struct job_ptr) {
   struct task_struct answer;

#pragma omp critical
   {
      if (job_ptr == NULL) answer = NULL;
      else {
         answer = (job_ptr)->task;
         job_ptr = (job_ptr)->next;
      }
   }
   return answer;
}
```

17.8.2 Function `omp_get_thread_num`

Earlier in this chapter we computed π using the rectangle rule. In Chapter 10 we computed π using the Monte Carlo method. The idea, illustrated in Figure 17.8, is to generate pairs of points in the unit square (where each coordinate varies between 0 and 1). We count the fraction of points inside the circle (those points for which $x^2 + y^2 \leq 1$). The expected value of this fraction is $\pi/4$; hence multiplying the fraction by 4 gives an estimate of π.

Here is the C code implementing the algorithm:

```
int      count;          /* Points inside unit circle */
unsigned short xi[3];    /* Random number seed */
int      i;
int      samples;        /* Points to generate */
double   x, y;           /* Coordinates of point */
samples = atoi (argv[1]);
xi[0] = atoi (argv[2]);
xi[1] = atoi (argv[3]);
```

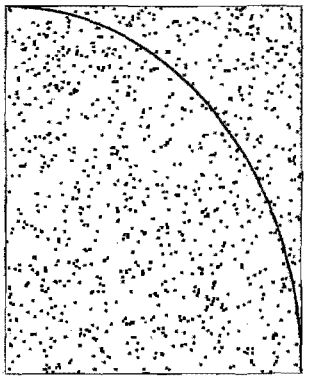


Figure 17.8 Example of a Monte Carlo algorithm to compute π. In this example we have generated 1,000 pairs from a uniform distribution between 0 and 1. Since 773 pairs are inside the unit circle, our estimate of π is 4(773/1000), or 3.092.

```
xi[2] = atoi (argv[4]);
count = 0;
for (i = 0; i < samples; i++) {
   x = erand48(xi);
   y = erand48(xi);
   if (x*x+y*y <= 1.0) count++;
}
printf ("Estimate of pi: %7.5f\n", 4.0*count/samples);
```

If we want to speed the execution of the program by using multiple threads, we must ensure that each thread is generating a different stream of random numbers. Otherwise, each thread would generate the same sequence of (x, y) pairs, and there would be no increase in the precision of the answer through the use of parallelism. Hence `xi` must be a private variable, and must find some way for each thread to initialize array `xi` with unique values. That means we need to have some way of distinguishing threads.

In OpenMP every thread on a multiprocessor has a unique identification number. We can retrieve this number using the function `omp_get_thread_num`, which has this header:

```
int omp_get_thread_num (void)
```

If there are t active threads, the thread identification numbers are integers ranging from 0 through $t - 1$. The master thread always has identification number 0.

Assigning the thread identification number to `xi[2]` ensures each thread has a different random number seed.

17.8.3 Function `omp_get_num_threads`

In order to divide the iterations among the threads, we must know the number of active threads. Function `omp_get_num_threads`, with this header

```
int omp_get_num_threads(void)
```

returns the number of threads active in the current parallel region. We can use this information, as well as the thread identification number, to divide the iterations among the threads.

Each thread will accumulate its count of points inside the circle in a private variable. When each thread completes the `for` loop, it will add its subtotal to `count` inside a critical section.

The OpenMP implementation of the Monte Carlo π-finding algorithm appears in Figure 17.9.

17.8.4 `for` Pragma

The `parallel` pragma can also come in handy when parallelizing `for` loops. Consider this doubly nested loop:

```
for (i = 0; i < m; i++) {
   low = a[i];
   high = b[i];
   if (low > high) {
      printf ("Exiting during iteration %d\n", i);
      break;
   }
   for (j = low; j < high; j++)
      c[j] = (c[j] - a[i])/b[i];
}
```

We cannot execute the iterations of the outer loop in parallel, because it contains a `break` statement. If we put a `parallel for` pragma before the loop indexed by `j`, there will be a fork/join step for every iteration of the outer loop. We would like to avoid this overhead. Previously, we showed how inverting `for` loops could solve this problem, but that approach doesn't work here because of the data dependences.

If we put the `parallel` pragma immediately in front of the loop indexed by `i`, then we'll only have a single fork/join. The default behavior is that *every* thread executes *all* of the code inside the block. Of course, we want the threads to divide up the iterations of the inner loop. The `for` pragma directs the compiler to do just that:

```
#pragma omp for
```

```
/*
 * OpenMP implementation of Monte Carlo pi-finding algorithm
 */

#include <stdio.h>
int main (int argc, char *argv[]){
   int      count;          /* Points inside unit circle */
   int      i;
   int      local_count;    /* This thread's subtotal */
   int      samples;        /* Points to generate */
   unsigned short xi[3];    /* Random number seed */
   int      t;              /* Number of threads */
   int      tid;            /* Thread id */
   double   x, y;           /* Coordinates of point */

   /* Number of points and number of threads are
      command-line arguments */

   samples = atoi(argv[1]);
   omp_set_num_threads (atoi(argv[2]));

   count = 0;
#pragma omp parallel private(xi,t,i,x,y,local_count)
   {
      local_count = 0;
      xi[0] = atoi(argv[3]);
      xi[1] = atoi(argv[4]);
      xi[2] = tid = omp_get_thread_num();
      t = omp_get_num_threads();

      for (i = tid; i < samples; i += t) {
         x = erand48(xi);
         y = erand48(xi);
         if (x*x+y*y <= 1.0) local_count++;
      }
#pragma omp critical
      count += local_count;
   }
   printf ("Estimate of pi: %7.5f\n", 4.0*count/samples);
}
```

Figure 17.9 This C/OpenMP program uses the Monte Carlo method to compute π.

With these pragmas added, our code segment looks like this:

```
#pragma omp parallel private(i,j)
for (i = 0; i < m; i++) {
   low = a[i];
   high = b[i];
   if (low > high) {
      printf ("Exiting during iteration %d\n", i);
      break;
   }
```

```
#pragma omp for
   for (j = low; j < high; j++)
      c[j] = (c[j] - a[i])/b[i];
}
```

Our work is not yet complete, however.

17.8.5 `single` Pragma

We have parallelized the execution of the loop indexed by `j`. What about the other code inside the outer loop? We certainly don't want to see the error message more than once.

The `single` pragma tells the compiler that only a single thread should execute the block of code the pragma precedes. Its syntax is:

```
#pragma omp single
```

Adding the `single` pragma to the code block, we now have:

```
#pragma omp parallel private(i,j)
for (i = 0; i < m; i++) {
   low = a[i];
   high = b[i];
   if (low > high) {
#pragma omp single
      printf ("Exiting during iteration %d\n", i);
      break;
   }
#pragma omp for
   for (j = low; j < high; j++)
      c[j] = (c[j] - a[i])/b[i];
}
```

The code block now executes correctly, but we can improve its performance.

17.8.6 `nowait` Clause

The compiler puts a barrier synchronization at the end of every `parallel for` statement. In the example we have been considering, this barrier is necessary, because we need to ensure that every thread has completed one iteration of the loop indexed by `i` before any thread begins the next iteration. Otherwise, a thread might change the value of `low` or `high`, altering the number of iterations of the `j` loop performed by another thread.

On the other hand, if we make `low` and `high` private variables, there is no need for the barrier at the end of the loop indexed by `j`. The `nowait` clause, added to a `parallel for` pragma, tells the compiler to omit the barrier synchronization at the end of the parallel `for` loop.

After making low and high private and adding the nowait clause, our final version of our example code segment is:

```
#pragma omp parallel private(i,j,low,high)
for (i = 0; i < m; i++) {
   low = a[i];
   high = b[i];
   if (low > high) {
#pragma omp single
      printf ("Exiting during iteration %d\n", i);
      break;
   }
#pragma omp for nowait
   for (j = low; j < high; j++)
      c[j] = (c[j] - a[i])/b[i];
}
```

17.9 FUNCTIONAL PARALLELISM

To this point we have focused entirely on exploiting data parallelism. Another source of concurrency is functional parallelism. OpenMP allows us to assign different threads to different portions of code.

Consider, for example, the following code segment:

```
v = alpha();
w = beta();
x = gamma(v, w);
y = delta();
printf ("%6.2f\n", epsilon(x,y));
```

If all of the functions are side-effect free, we can represent the data dependences as shown in Figure 17.10. Clearly functions alpha, beta, and delta may be executed in parallel. If we execute these functions concurrently, there is no more

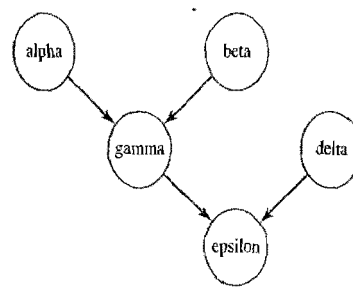


Figure 17.10 Data dependence diagram for code segment of Section 17.9.

functional parallelism to exploit, because function gamma must be called after functions alpha and beta and before function epsilon.

17.9.1 parallel sections Pragma

The parallel sections pragma precedes a block of k blocks of code that may be executed concurrently by k threads. It has this syntax:

```
#pragma omp parallel sections
```

17.9.2 section Pragma

The section pragma precedes each block of code within the encompassing block preceded by the parallel sections pragma. (The section pragma may be omitted for the first parallel section after the parallel sections pragma.)

In the example we considered, the calls to functions alpha, beta, and delta could be evaluated concurrently. In our parallelization of this code segment, we use curly braces to create a block of code containing these three assignment statements. (Recall that an assignment statement is a trivial example of a code block. Hence a block containing three assignment statements is a block of three blocks of code.)

```
#pragma omp parallel sections
   {
#pragma omp section      /* This pragma optional */
      v = alpha();
#pragma omp section
      w = beta();
#pragma omp section
      y = delta();
   }
   x = gamma(v, w);
   printf ("%6.2f\n", epsilon(x,y));
```

Note that we reordered the assignment statements to bring together the three that could be executed in parallel.

17.9.3 sections Pragma

Let's take another look at the data dependence diagram of Figure 17.10. There is a second way to exploit functional parallelism in this code segment. As we noted earlier, if we execute functions alpha, beta, and delta in parallel, there are no further opportunities for functional parallelism. However, if we execute only functions alpha and beta in parallel, then after they return we may execute functions gamma and delta in parallel.

In this design we have two different parallel sections, one following the other. We can reduce fork/join costs by putting all four assignment statements in a single

block preceded by the `parallel` pragma, then using the `sections` pragma to identify the first and second pairs of functions that may execute in parallel.

The `sections` pragma with syntax

```
#pragma omp sections
```

appears inside a `parallel` block of code. It has exactly the same meaning as the `parallel sections` pragma we have already described.

Here is another way to express functional parallelism in the code segment we have been considering, using the `sections` pragma:

```
#pragma omp parallel
   {
   #pragma omp sections
      {
      #pragma omp section      /* This pragma optional */
         v = alpha();
      #pragma omp section
         w = beta();
      }
   #pragma omp sections
      {
      #pragma omp section     /* This pragma optional */
         x = gamma(v, w);
      #pragma omp section
         y = delta();
      }
   }
   printf ("%6.2f\n", epsilon(x,y));
```

In one respect this solution is better than the first one we presented, because it has two parallel sections of code, each requiring two threads. Our first solution has only a single parallel section of code that required three threads. If only two processors are available, the second section of code could result in higher efficiency. Whether or not that is the case depends upon the execution times of the individual functions.

17.10 SUMMARY

OpenMP is an API for shared-memory parallel programming. The shared-memory model relies upon fork/join parallelism. You can envision the execution of a shared-memory program as periods of sequential execution alternating with periods of parallel execution. A master thread executes all of the sequential code. When it reaches a parallel code segment, it forks other threads. The threads communicate with each other via shared variables. At the end of the parallel code segment, these threads synchronize, rejoining the master thread.

This chapter has introduced OpenMP pragmas and clauses that can be used to transform a sequential C program into one that runs in parallel on a multiprocessor. First we considered the parallelization of `for` loops. In C programs data parallelism is often expressed in the form of `for` loops. We use the `parallel for` pragma to indicate to the compiler those loops whose iterations may be performed in parallel. There are certain restrictions on `for` loops that may be executed in parallel. The control clause must be simple, so that the run-time system can determine, before the loop executes, how many iterations it will have. The loop cannot have a `break` statement, `goto` statement, or another statement that allows early loop termination.

We also discussed how to take advantage of functional parallelism through the use of the `parallel sections` pragma. This pragma precedes a block of blocks of code, where each of the inner blocks, or sections, represents an independent task that may be performed in parallel with the other sections.

The `parallel` pragma precedes a block of code that should be executed in parallel by all threads. When all threads execute the same code, the result is SPMD-style parallel execution similar to that exhibited by many of our programs using MPI. A `for` pragma or a `sections` pragma may appear inside the block of code marked with a `parallel` pragma, allowing the compiler to exploit data or functional parallelism.

We also use pragmas to point out areas within parallel sections that must be executed sequentially. The `critical` pragma indicates a block of code forming a critical section where mutual exclusion must be enforced. The `single` pragma indicates a block of code that should only be executed by one of the threads.

We can convey additional information to the compiler by adding clauses to pragmas. The `private` clause gives each thread its own copy of the listed variables. Values can be copies between the original variable and private variables using the `firstprivate` and/or the `lastprivate` clauses. The `reduction` clause allows the compiler to generate efficient code for reduction operations happening inside a parallel loop. The `schedule` clause lets you specify the way loop iterations are allocated to tasks. The `if` clause allows the system to determine at run-time if a construct should be executed sequentially or by multiple threads. The `nowait` clause eliminates the barrier synchronization at the end of the parallel construct.

While we have introduced clauses in the context of particular pragmas, most clauses can be applied to most pragmas. Table 17.4 lists which of the clauses we have introduced in this chapter may be attached to which pragmas.

We have examined various ways in which the performance of parallel `for` loops can be enhanced. The strategies are inverting loops, conditionally parallelizing loops, and changing the way in which loop iterations are scheduled.

Table 17.5 compares OpenMP with MPI. Both programming environments can be used to program multiprocessors. MPI is suitable for programming multicomputers. Since OpenMP has shared variables, OpenMP is not appropriate for generic multicomputers in which there is no shared memory. MPI also makes it easier for the programmer to take control of the memory hierarchy. On the

Table 17.4 This table summarizes which clauses may be attached to which pragmas.

Pragma	Clauses allowed
`critical`	*None*
`for`	`firstprivate, lastprivate, nowait, private, reduction, schedule`
`parallel`	`firstprivate, if, lastprivate, private, reduction`
`parallel for`	`firstprivate, if, lastprivate, private, reduction, schedule`
`parallel sections`	`firstprivate, if, lastprivate, private, reduction`
`sections`	`firstprivate, lastprivate, nowait, private, reduction`
`single`	`firstprivate, nowait, private`

Note: OpenMP has additional clauses not introduced in this chapter.

Table 17.5 Comparison of OpenMP and MPI.

Characteristic	OpenMP	MPI
Suitable for multiprocessors	Yes	Yes
Suitable for multicomputers	No	Yes
Supports incremental parallelization	Yes	No
Minimal extra code	Yes	No
Explicit control of memory hierarchy	No	Yes

other hand, OpenMP has the significant advantage of allowing programs to be incrementally parallelized. In addition, unlike programs using MPI, which often are much longer than their sequential counterparts, programs using OpenMP are usually not much longer than the sequential codes they displace.

17.11 KEY TERMS

canonical shape
chunk
clause
critical section
dynamic schedule
execution context
fork/join parallelism
grain size
guided self-scheduling
incremental parallelization
master thread
pragma
`private` clause
private variable
race condition
reduction variable
schedule
sequentially last iteration
shared variable
static schedule

17.12 BIBLIOGRAPHIC NOTES

The URL for the official OpenMP Web site is `www.OpenMP.org`. You can download the official OpenMP specifications for the C/C++ and Fortran versions of OpenMP from this site.

Parallel Programming in OpenMP by Chandra et al. is an excellent introduction to this shared-memory application programming interface [16]. It provides broader and deeper coverage of the features of OpenMP. It also discusses performance tuning of OpenMP codes.

17.13 EXERCISES

17.1 Of the four OpenMP functions presented in this chapter, which two have the closest analogs to MPI functions? Name the MPI function each of these functions is similar to.

17.2 For each of the following code segments, use OpenMP pragmas to make the loop parallel, or explain why the code segment is not suitable for parallel execution.

a.
```
for (i = 0; i < (int) sqrt(x); i++) {
   a[i] = 2.3 * i;
   if (i < 10) b[i] = a[i];
}
```

b.
```
flag = 0;
for (i = 0; (i < n) & (!flag); i++) {
   a[i] = 2.3 * i;
   if (a[i] < b[i]) flag = 1;
}
```

c.
```
for (i = 0; i < n; i++)
   a[i] = foo(i);
```

d.
```
for (i = 0; i < n; i++) {
   a[i] = foo(i);
   if (a[i] < b[i]) a[i] = b[i];
}
```

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

f.
```
dotp = 0;
for (i = 0; i < n; i++)
   dotp += a[i] * b[i];
```

g.
```
for (i = k; i < 2*k; i++)
   a[i] = a[i] + a[i-k];
```