Parallel Programming
in C with MPI and OpenMP

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Chapter 17
Shared-memory Programming

Outline

- OpenMP
- Shared-memory model
- Parallel for loops
- Declaring private variables
- Critical sections
- Reductions
- Performance improvements
- More general data parallelism
- Functional parallelism

OpenMP

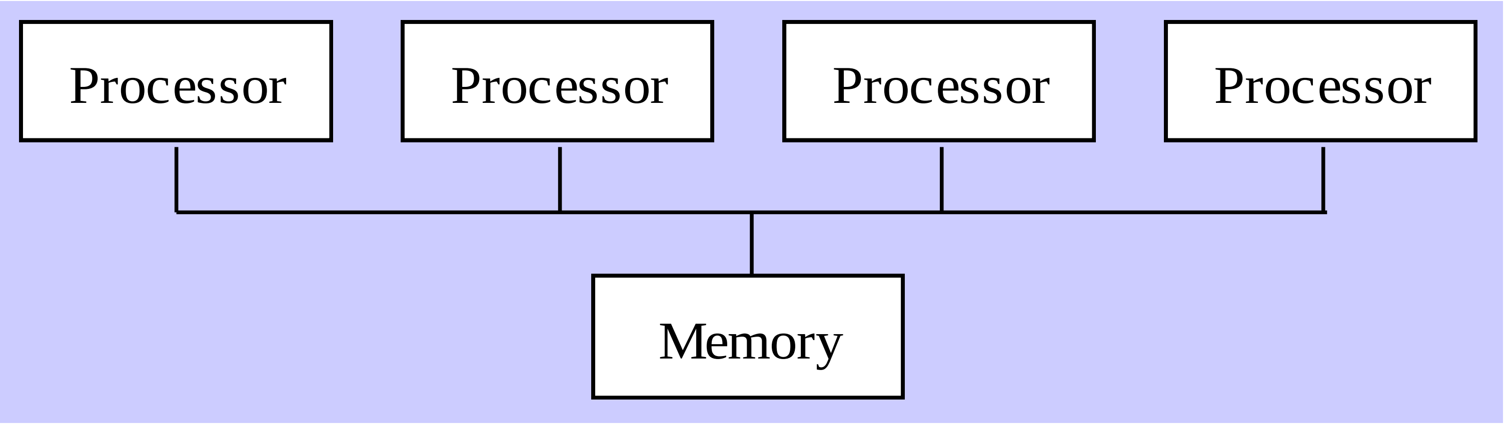
- OpenMP: An application programming interface (API) for parallel programming on multiprocessors
  - Compiler directives
  - Library of support functions
- OpenMP works in conjunction with Fortran, C, or C++

What's OpenMP Good For?

- C + OpenMP sufficient to program multiprocessors
- C + MPI + OpenMP a good way to program multicomputers built out of multiprocessors
  - IBM RS/6000 SP
  - Fujitsu AP3000
  - Dell High Performance Computing Cluster

Compare OpenMP with multi-thread programming.

Shared-memory Model

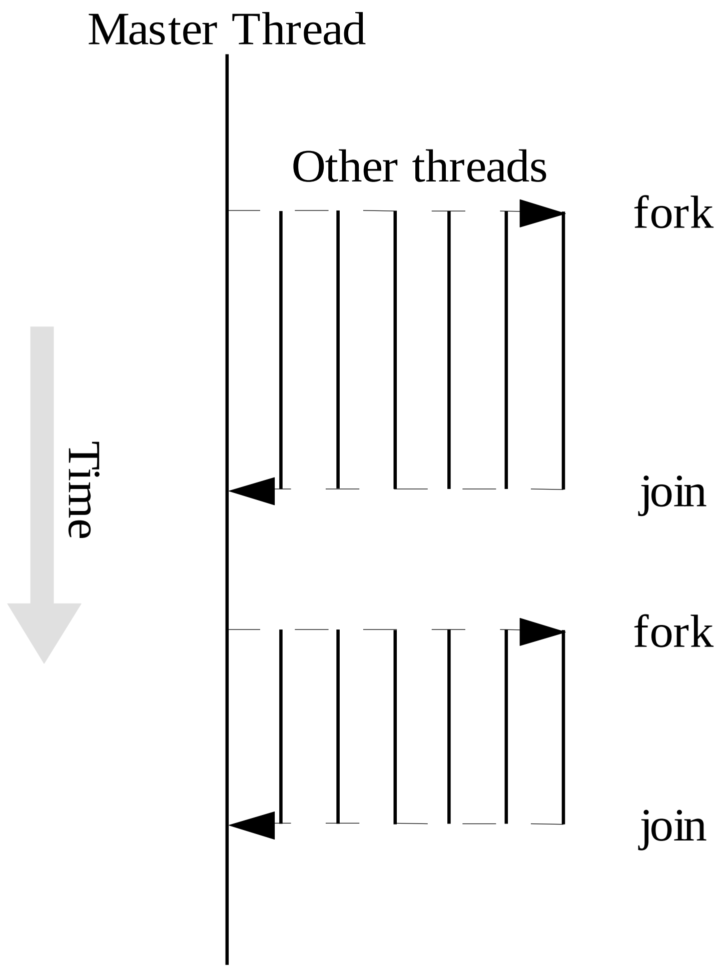


- Processors interact and synchronize with each other through shared variables.

Fork/Join Parallelism

- Initially only master thread is active
- Master thread executes sequential code
- Fork: Master thread creates or awakens additional threads to execute parallel code
- Join: At end of parallel code created threads die or are suspended, the flow of control returns to the master thread

Fork/Join Parallelism



Shared-memory Model vs. Message-passing Model (#1)

- Shared-memory model
  - Number active threads: 1 at start and finish of program, changes dynamically during execution
- Message-passing model
  - All processes active throughout execution of program

Incremental Parallelization

- Sequential program a special case of a shared-memory parallel program
- Parallel shared-memory programs may only have a single parallel loop
- Incremental parallelization: process of converting a sequential program to a parallel program a little bit at a time

Shared-memory Model vs. Message-passing Model (#2)

- Shared-memory model
  - Execute and profile sequential program
  - Incrementally make it parallel
  - Stop when further effort not warranted
- Message-passing model
  - Sequential-to-parallel transformation requires major effort
  - Transformation done in one giant step rather than many tiny steps

Parallel `for` Loops

- C programs often express data-parallel operations as **`for`** loops

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

- OpenMP makes it easy to indicate when the iterations of a loop may execute in parallel
- Compiler takes care of generating code that forks/joins threads and allocates the iterations to threads

Pragmas

- Pragma: a compiler directive in C or C++
- Stands for “pragmatic information”
- A way for the programmer to communicate with the compiler
- Compiler free to ignore pragmas
- Syntax:
  `#pragma omp <rest of pragma>`

Parallel for Pragma

- Format:

```
#pragma omp parallel for
for (i = 0; i < N; i++)
    a[i] = b[i] + c[i];
```

- Compiler must be able to verify the run-time system will have information it needs to schedule loop iterations

Canonical Shape of `for` Loop Control Clause

$$\text{for}(\text{index} = start;\text{index}\begin{Bmatrix} < \\ <= \\ >= \\ > \end{Bmatrix} end;\begin{Bmatrix} \text{index}++ \\ ++\text{index} \\ \text{index}-- \\ --\text{index} \\ \text{index}+=inc \\ \text{index}-=inc \\ \text{index}=\text{index}+inc \\ \text{index}=inc+\text{index} \\ \text{index}=\text{index}-inc \end{Bmatrix})$$

Execution Context

- Every thread has its own execution context
- Execution context: address space containing all of the variables a thread may access
- Contents of execution context:
  - static variables
  - dynamically allocated data structures in the heap
  - variables on the run-time stack
  - additional run-time stack for functions invoked by the thread

Shared and Private Variables

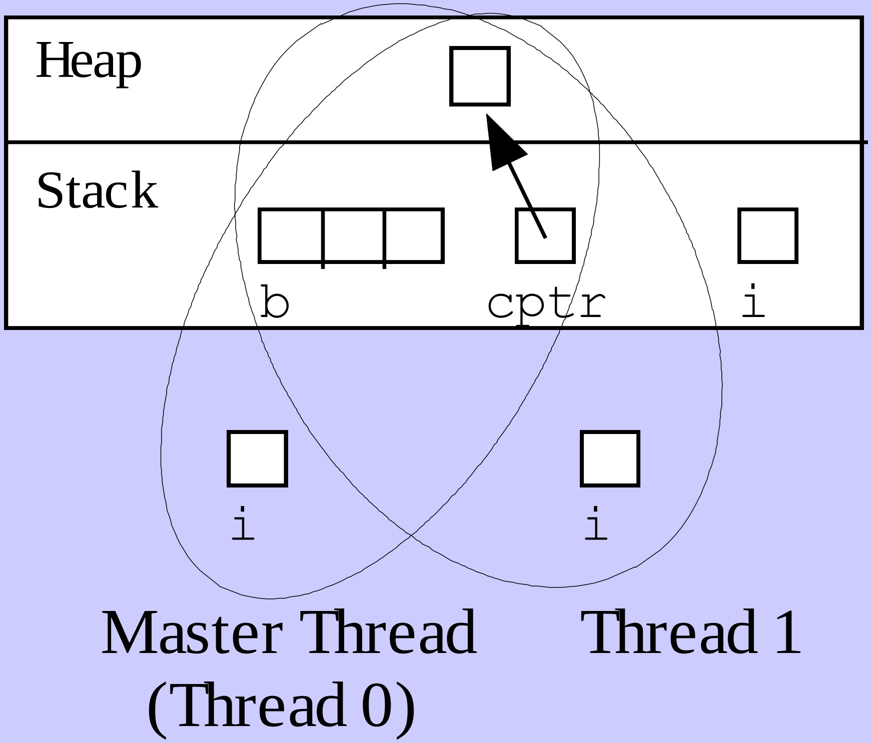
- Shared variable: has same address in execution context of every thread
- Private variable: has different address in execution context of every thread
- A thread cannot access the private variables of another thread

Similar to the concept of light weight process

Shared and Private Variables

```
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;
```



Function `omp_get_num_procs`

- Returns number of physical processors available for use by the parallel program

```
int omp_get_num_procs(void)
```

Function `omp_set_num_threads`

- Uses the parameter value to set the number of threads to be active in parallel sections of code
- May be called at multiple points in a program

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

Pop Quiz:

- Write a C program segment that sets the number of threads equal to the number of processors that are available.

Declaring Private Variables

```
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);
```

- Either loop could be executed in parallel
- We prefer to make outer loop parallel, to reduce number of forks/joins
- We then must give each thread its own private copy of variable j

private Clause

- Clause: an optional, additional component to a pragma
- Private clause: directs compiler to make one or more variables private

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

Example Use of private Clause

```
#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);
```

`firstprivate` Clause

- Used to create private variables having initial values identical to the variable controlled by the master thread as the loop is entered
- Variables are initialized once per thread, not once per loop iteration
- If a thread modifies a variable's value in an iteration, subsequent iterations will get the modified value

`lastprivate` Clause

- Sequentially last iteration: iteration that occurs last when the loop is executed sequentially
- **`lastprivate`** clause: used to copy 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

Critical Sections

```
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;
```

Race Condition

- Consider this C program segment to compute π using 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;
```

Race Condition (cont.)

- 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);
}
pi = area / n;
```

Race Condition (cont.)

- ... we set up a race condition in which one process may “race ahead” of another and not see its change to shared variable area

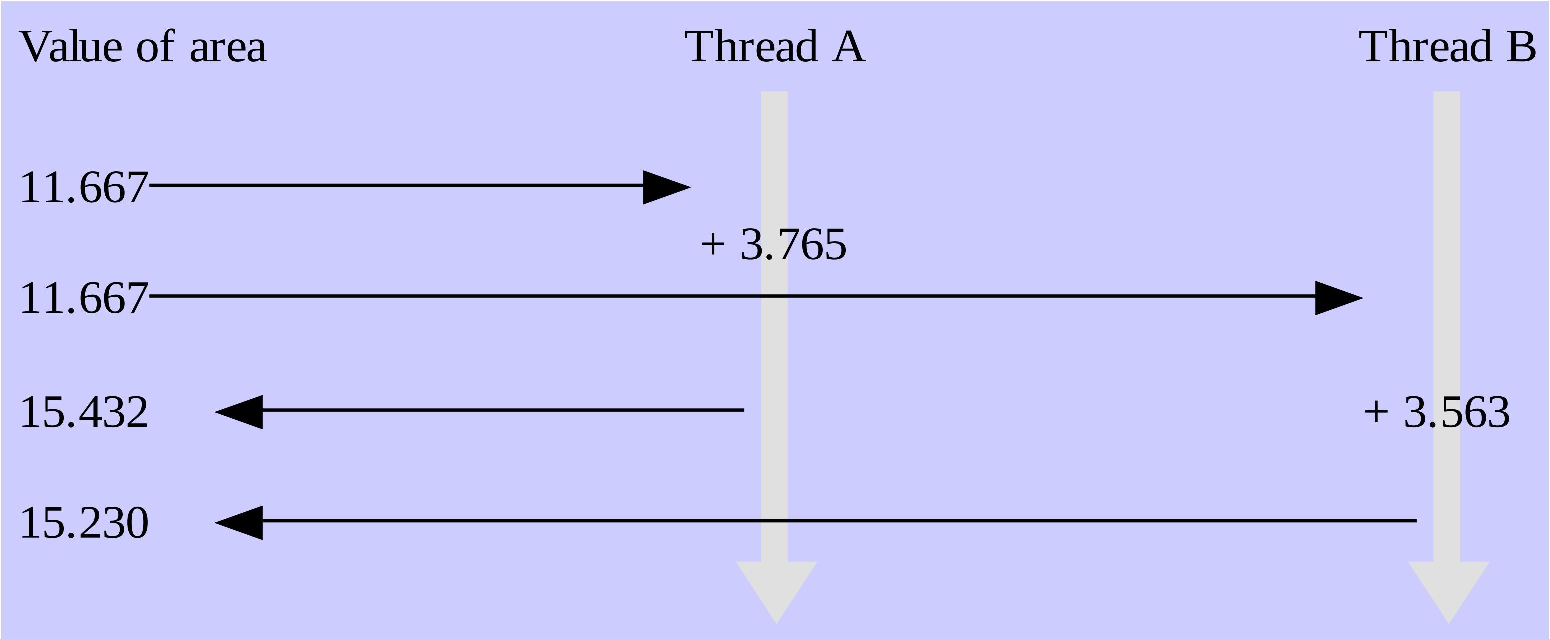
`area` 15.230 **Answer should be 18.995**

Thread A 15.432

Thread B 15.230

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

Race Condition Time Line



critical Pragma

- Critical section: a portion of code that only thread at a time may execute
- We denote a critical section by putting the pragma

```
#pragma omp critical
```

in front of a block of C code

Correct, But Inefficient, Code

```
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;
```

Source of Inefficiency

- Update to area inside a critical section
- Only one thread at a time may execute the statement; i.e., it is sequential code
- Time to execute statement significant part of loop
- By Amdahl's Law we know speedup will be severely constrained

Reductions

- Reductions are so common that OpenMP provides support for them
- May add reduction clause to parallel for pragma
- Specify reduction operation and reduction variable
- OpenMP takes care of storing partial results in private variables and combining partial results after the loop

reduction Clause

- The reduction clause has this syntax:

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

<table>
<tr><th>Operator</th><th>Meaning</th><th>Allowable types</th><th>Initial value</th></tr>
<tr><td>+</td><td>Sum</td><td>float, int</td><td>0</td></tr>
<tr><td>*</td><td>Product</td><td>float, int</td><td>1</td></tr>
<tr><td>&</td><td>Bitwise and</td><td>int</td><td>all bits 1</td></tr>
<tr><td>|</td><td>Bitwise or</td><td>int</td><td>0</td></tr>
<tr><td>^</td><td>Bitwise exclusive or</td><td>int</td><td>0</td></tr>
<tr><td>&&</td><td>Logical and</td><td>int</td><td>1</td></tr>
<tr><td>||</td><td>Logical or</td><td>int</td><td>0</td></tr>
</table>

π-finding Code with Reduction Clause

```
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;
```

Performance Improvement #1

- Too many fork/joins can lower performance
- Inverting loops may help performance if
  - Parallelism is in inner loop
  - After inversion, the outer loop can be made parallel
  - Inversion does not significantly lower cache hit rate

Performance Improvement #2

- If loop has too few iterations, fork/join overhead is greater than time savings from parallel execution
- The if clause instructs compiler to insert code that determines at run-time whether loop should be executed in parallel; e.g.,

```
#pragma omp parallel for if(n > 5000)
```

Performance Improvement #3

- We can use schedule clause to specify how iterations of a loop should be allocated to threads
- Static schedule: all iterations allocated to threads before any iterations executed
- Dynamic schedule: only some iterations allocated to threads at beginning of loop's execution. Remaining iterations allocated to threads that complete their assigned iterations.

Static vs. Dynamic Scheduling

- Static scheduling
  - Low overhead
  - May exhibit high workload imbalance
- Dynamic scheduling
  - Higher overhead
  - Can reduce workload imbalance

Chunks

- A chunk is a contiguous range of iterations
- Increasing chunk size reduces overhead and may increase cache hit rate
- Decreasing chunk size allows finer balancing of workloads

`schedule` Clause

- Syntax of schedule clause
  `schedule (<type>[,<chunk> ])`
- Schedule type required, chunk size optional
- Allowable schedule types
  - static: static allocation
  - dynamic: dynamic allocation
  - guided: guided self-scheduling
  - runtime: type chosen at run-time based on value of environment variable OMP_SCHEDULE

Scheduling Options

- schedule(static): block allocation of about n/t contiguous iterations to each thread
- schedule(static,C): interleaved allocation of chunks of size C to threads
- schedule(dynamic): dynamic one-at-a-time allocation of iterations to threads
- schedule(dynamic,C): dynamic allocation of C iterations at a time to threads

Scheduling Options (cont.)

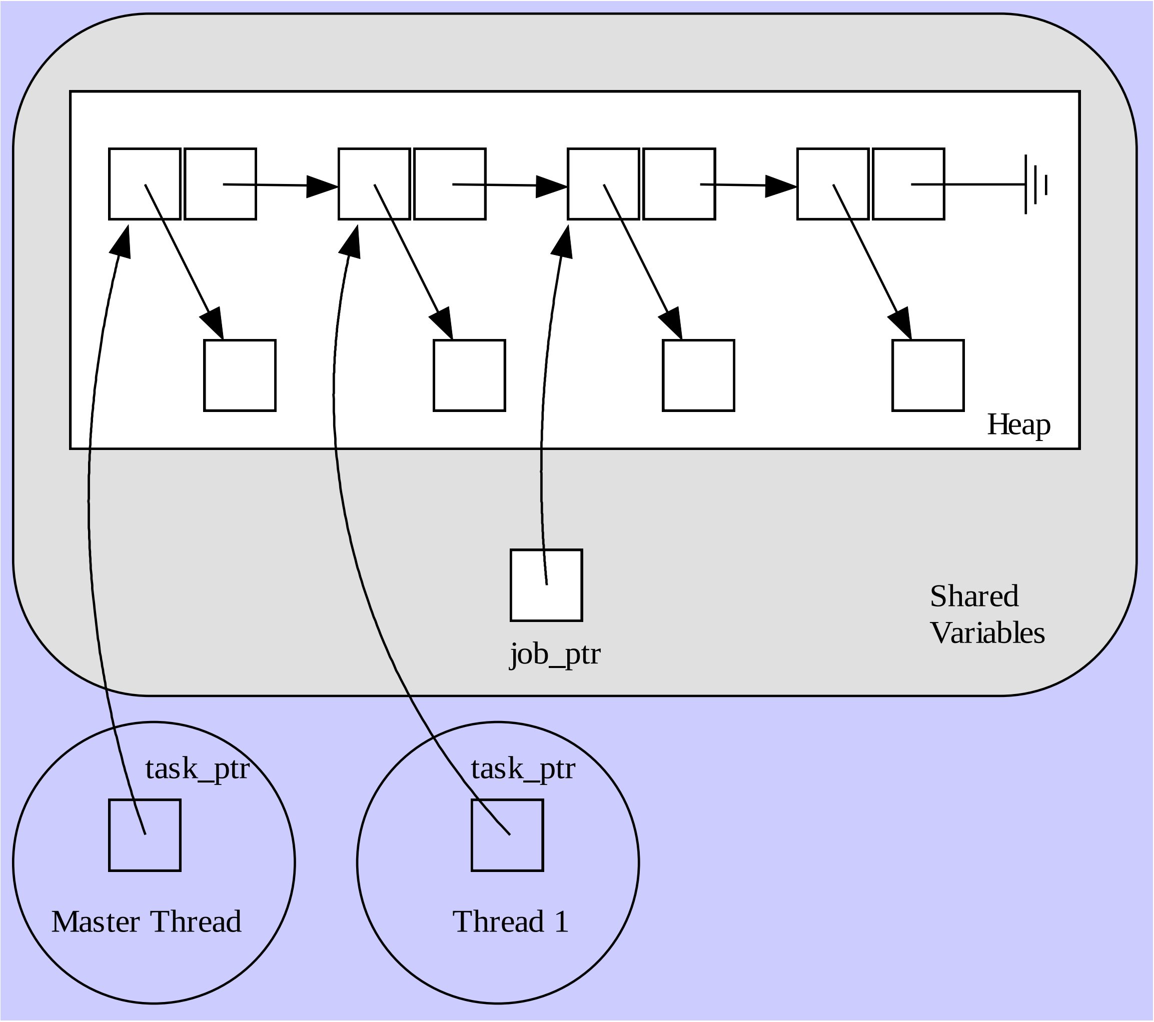
- schedule(guided, C): dynamic allocation of chunks to tasks using guided self-scheduling heuristic. Initial chunks are bigger, later chunks are smaller, minimum chunk size is C.
- schedule(guided): guided self-scheduling with minimum chunk size 1
- schedule(runtime): schedule chosen at run-time based on value of OMP_SCHEDULE; Unix example:

```
setenv OMP_SCHEDULE “static,1”
```

More General Data Parallelism

- Our focus has been on the parallelization of `for` loops
- Other opportunities for data parallelism
  - processing items on a “to do” list
  - for loop + additional code outside of loop

Processing a “To Do” List



Sequential Code (1/2)

```
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);
   }
   ...
}
```

Sequential Code (2/2)

```
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;
}
```

Parallelization Strategy

- Every thread should repeatedly take next task from list and complete it, until there are no more tasks
- We must ensure no two threads take same take from the list; i.e., must declare a critical section

`parallel` Pragma

- The **`parallel`** pragma precedes a block of code that should be executed by all of the threads
- Note: execution is replicated among all threads

Use of `parallel` Pragma

```
#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);
   }
}
```

Critical Section for `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;
}
```

Functions for SPMD-style Programming

- The parallel pragma allows us to write SPMD-style programs
- In these programs we often need to know number of threads and thread ID number
- OpenMP provides functions to retrieve this information

Function omp_get_thread_num

- This function returns the thread identification number
- If there are t threads, the ID numbers range from 0 to $t-1$
- The master thread has ID number 0

```
int omp_get_thread_num(void)
```

Function omp_get_num_threads

- Function omp_get_num_threads returns the number of active threads
- If call this function from sequential portion of program, it will return 1

```
int omp_get_num_threads(void)
```

`for` Pragma

- The **`parallel`** pragma instructs every thread to execute all of the code inside the block
- If we encounter a **`for`** loop that we want to divide among threads, we use the **`for`** pragma

```
#pragma omp for
```

Example Use of `for` Pragma

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

`single` Pragma

- Suppose we only want to see the output once
- The single pragma directs compiler that only a single thread should execute the block of code the pragma precedes
- Syntax:

```
#pragma omp single
```

Use of `single` Pragma

```
#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 (%d)\n", i);
      break;
   }
#pragma omp for
   for (j = low; j < high; j++)
      c[j] = (c[j] - a[i])/b[i];
}
```

`nowait` Clause

- Compiler puts a barrier synchronization at end of every parallel for statement
- In our example, this is necessary: if a thread leaves loop and changes low or high, it may affect behavior of another thread
- If we make these private variables, then it would be okay to let threads move ahead, which could reduce execution time

Use of `nowait` Clause

```
#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 (%d)\n", i);
      break;
   }
#pragma omp for nowait
   for (j = low; j < high; j++)
      c[j] = (c[j] - a[i])/b[i];
}
```

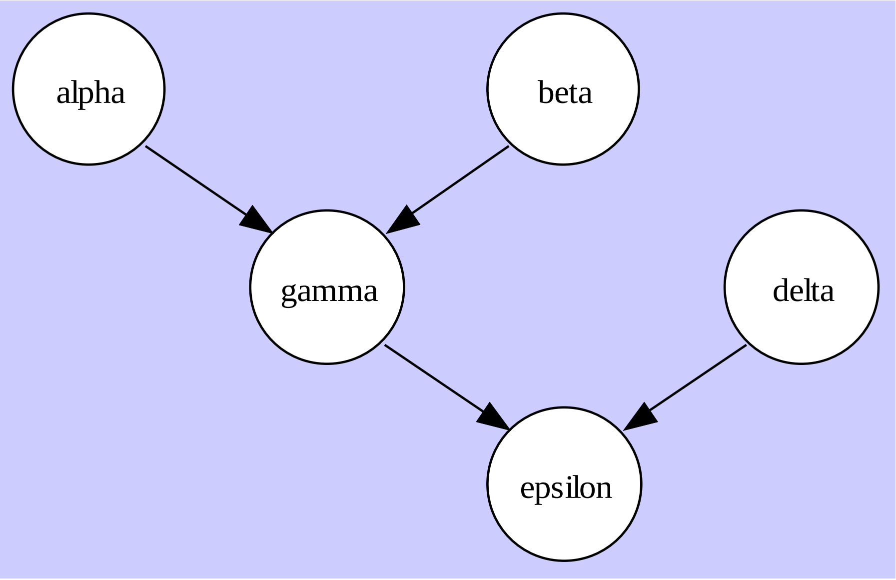
Functional Parallelism

- To this point all of our focus has been on exploiting data parallelism
- OpenMP allows us to assign different threads to different portions of code (functional parallelism)

Functional Parallelism Example

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

May execute alpha, beta, and delta in parallel



parallel sections Pragma

- Precedes a block of k blocks of code that may be executed concurrently by k threads
- Syntax:

```
#pragma omp parallel sections
```

section Pragma

- Precedes each block of code within the encompassing block preceded by the parallel sections pragma
- May be omitted for first parallel section after the parallel sections pragma
- Syntax:

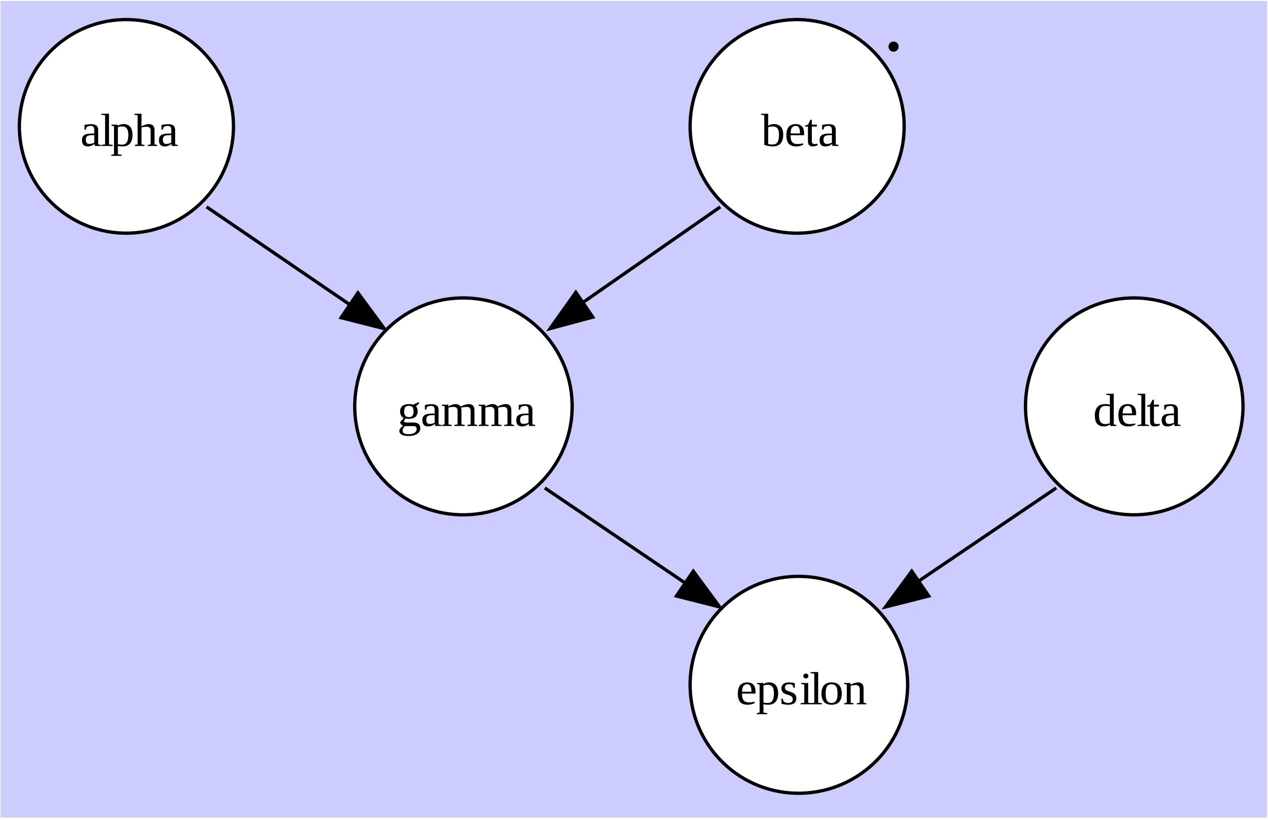
```
#pragma omp section
```

Example of `parallel sections`

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

Another Approach

- Execute alpha and beta in parallel.
- Execute gamma and delta in parallel



sections Pragma

- Appears inside a parallel block of code
- Has same meaning as the **`parallel sections`** pragma
- If multiple **`sections`** pragmas inside one parallel block, may reduce fork/join costs

Use of sections Pragma

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

Summary (1/3)

- OpenMP an API for shared-memory parallel programming
- Shared-memory model based on fork/join parallelism
- Data parallelism
  - parallel for pragma
  - reduction clause

Summary (2/3)

- Functional parallelism (parallel sections pragma)
- SPMD-style programming (parallel pragma)
- Critical sections (critical pragma)
- Enhancing performance of parallel for loops
  – Inverting loops
  – Conditionally parallelizing loops
  – Changing loop scheduling

Summary (3/3)

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