Multicore Programming Course

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Shared Memory Programming

Some Slides come From Parallel Programmingin C with MPI and OpenMP By Michael J. Quinn

&

An Overview of OpenMP

By Ruud van der Pas – Sun Microsystems

Introduction to OpenMP

- What is OpenMP?
  - Open specification for Multi-Processing
  - "Standard" API for defining multi-threaded shared-memory programs
  - openmp.org – Talks, examples, forums, etc.
- High-level API
  - Preprocessor (compiler) directives (~ 80%)
  - Library Calls (~ 19%)
  - Environment Variables (~ 1%)

A Programmer's View of OpenMP

- OpenMP is a portable, threaded, shared-memory programming *specification* with "light" syntax
  - Exact behavior depends on OpenMP *implementation*!
  - Requires compiler support (C or Fortran)
- OpenMP will:
  - Allow a programmer to separate a program into *serial regions* and *parallel regions,* rather than T concurrently-executing threads.
  - Hide stack management
  - Provide synchronization constructs
- OpenMP will not:
  - Parallelize automatically
  - Guarantee speedup
  - Provide freedom from data races

Motivation

- Thread libraries are hard to use
  - PThreads/Solaris threads have many library calls for initialization, synchronization, thread creation, condition variables, etc.
  - Programmer must code with multiple threads in mind
- Synchronization between threads introduces a new dimension of program correctness

- Wouldn't it be nice to write serial programs and somehow parallelize them "automatically"?
  - OpenMP can parallelize many serial programs with relatively few annotations that specify parallelism and independence
  - It is not automatic: you can still make errors in your annotations

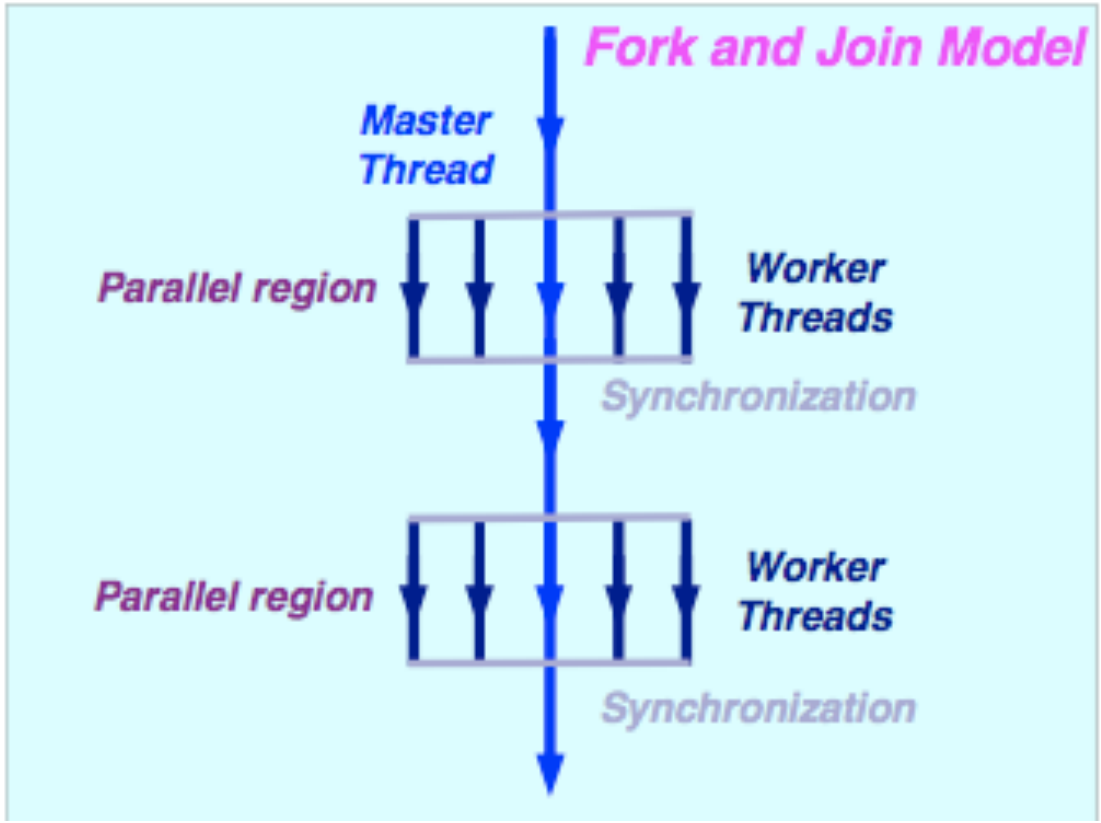
Motivation (Cont'd)

- Good performance and scalability
  - If you do it right ....
- De-facto standard
- An OpenMP program is portable
  - Supported by a large number of compilers
- Requires little programming effort
- Allows the program to be parallelized incrementally
- Maps naturally onto a multicore architecture:
  - Lightweight
  - Each OpenMP thread in the program can be executed by a hardware thread

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 OpenMP Execution Model



What's OpenMP Good For?

- C + OpenMP sufficient to program multiprocessors
- C + MPI + OpenMP a good way to program multicomputers built out of multiprocessors

A first OpenMP example

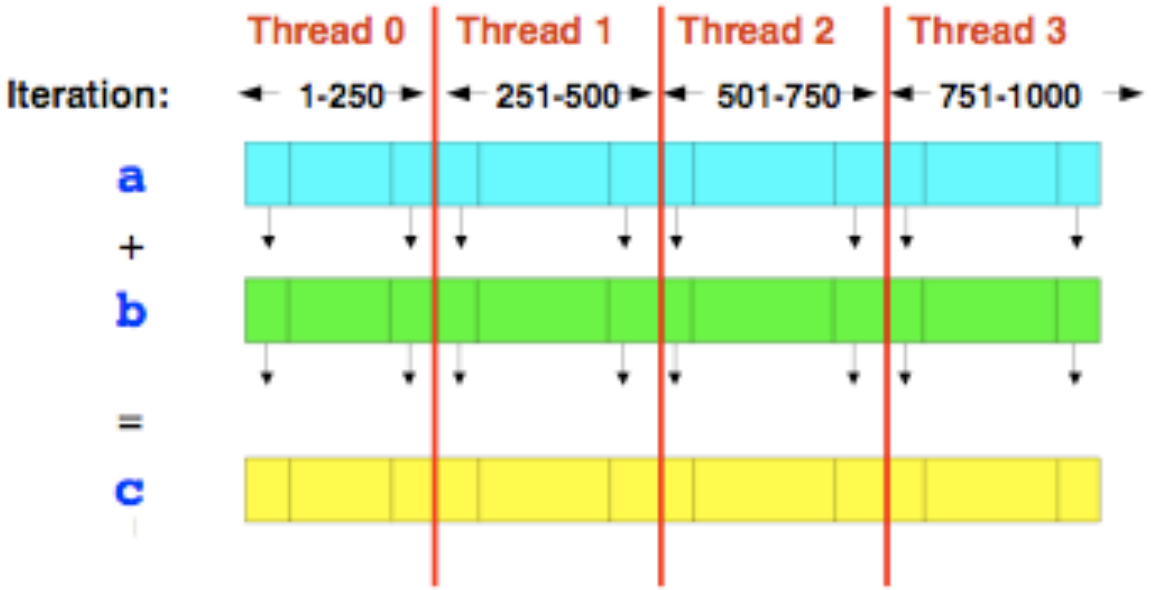
for-loop with independent Iteration

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

for-loop parallelized using OpenMP pragma

```
#pragma omp parallel for    \
        shared(n, a, b, c)  \
        private(i)
for (i = 0; i < n; i++)
        c[i] = a[i] + b[i];
```

Example Parallel Execution



Terminology

- OpenMP Team := Master + Workers
- A Parallel Region is a block of code executed by all threads simultaneously
  - The master thread always has thread ID 0
  - Parallel regions can be nested, but support for this is implementation dependent
  - An "if" clause can be used to guard the parallel region; in case the condition evaluates to "false", the code is executed serially
- A work-sharing construct divides the execution of the enclosed code region among the members of the team; in other words: they split the work

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

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

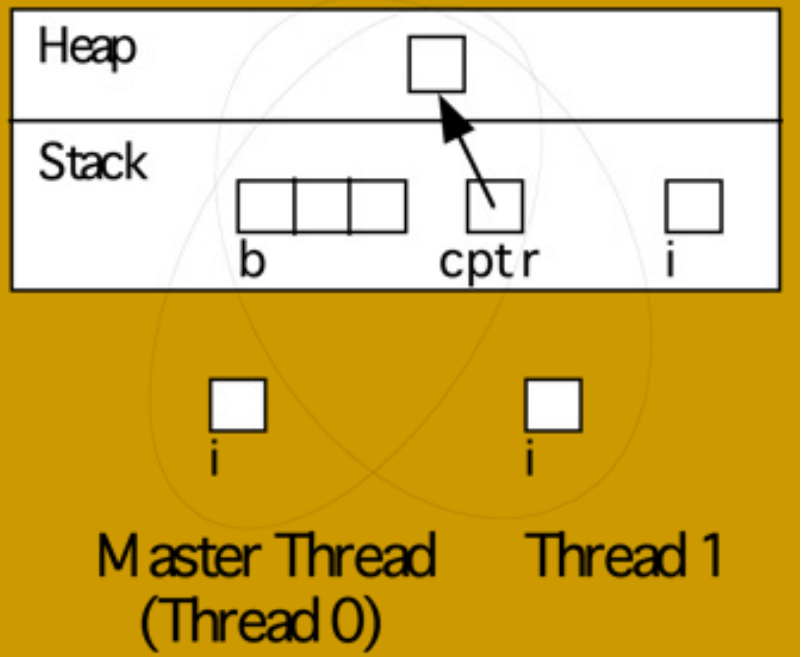
Shared and Private Variables

- 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

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;
```



Number of threads

- In unix, the environment variable OMP_NUM_THREADS provides a default number of threads.
- The number of threads is important. Each thread incurs an overhead. Too many threads may actually slow down the execution of a program.

The if/private/shared clauses

- **If Clause**
  - Only executes in parallel if expression evaluates to true
  - Otherwise, executes serially
- **private (list)**
  - No storage association with original object
  - All references are to the local object
  - Values are undefined on entry and exit

```
#pragma omp parallel if (n > threshold) \
            shared(n,x,y) private(i)
{
#pragma omp for
for (i=0; i<n; i++)
            x[i] += y[i];
} /*-- End of parallel region --*/
```

- **shared (list)**
  - Data is accessible by all threads in the team
  - All threads access the same address space

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[j]);
```

About storage association

- Private variables are undefined on entry and exit of the parallel region
- The value of the original variable (before the parallel region) is undefined after the parallel region !
- A private variable within a parallel region has no storage association with the same variable outside of the region
- Use the first/last private clause to override this behavior
- We illustrate these concepts with an example

firstprivate Clause

- Used to create private variables having initial values identical to the variable controlled by the master thread as the loop is entered (the value the original object had before entering the parallel construct)
- 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

Example firstprivate

```
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];
}
```

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:

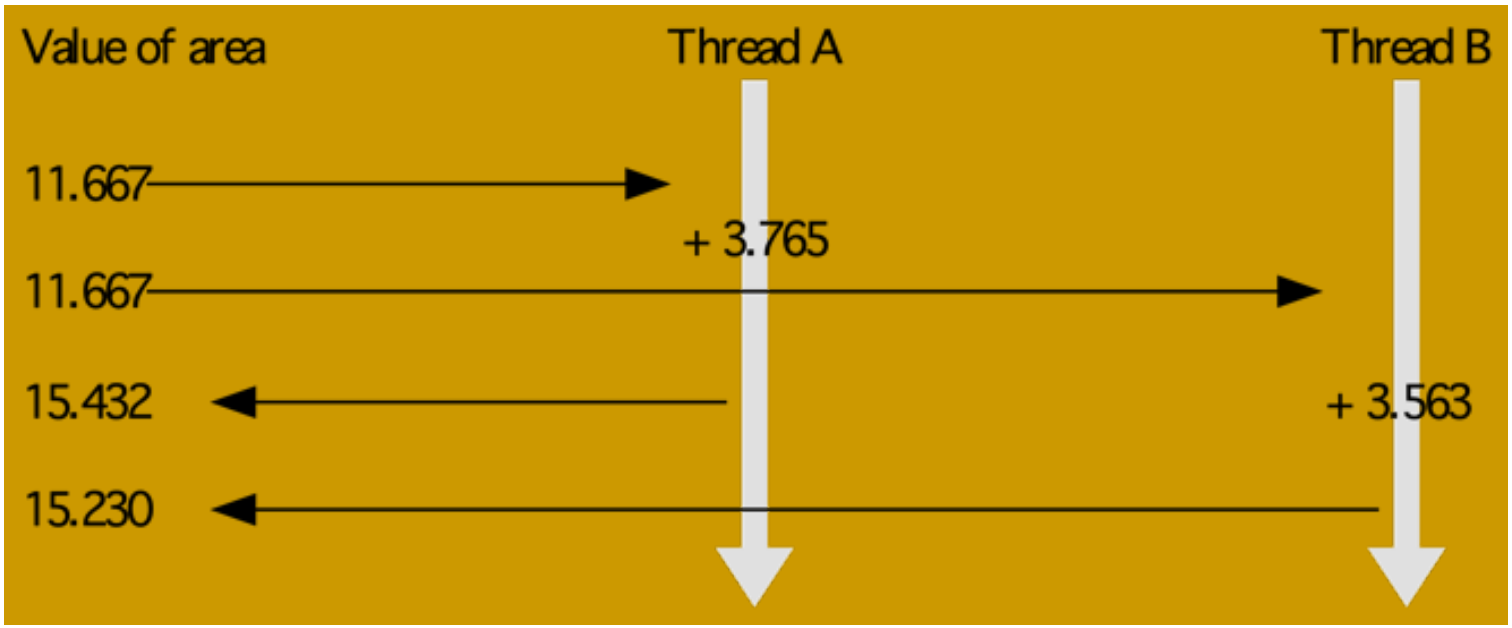
```
double area, pi, x;
int i, n;
...
area = 0.0;
for (i = 0; i < n; i++) {
   x = (i+0.5)/n;
   area += 4.0/(1.0 + x*x);
}
pi = area / n;
```

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 Time Line



critical Pragma

- Critical section: a portion of code that only one 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>)`
- Operators
  - + Sum
  - * Product
  - & Bitwise and
  - | Bitwise or
  - ^ Bitwise exclusive or
  - && Logical and
  - || Logical or

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;
```

Barrier

Suppose we run each of these two loops in parallel over i:

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

```
for (i=0; i < N; i++)
        d[i] = a[i] + b[i];
```

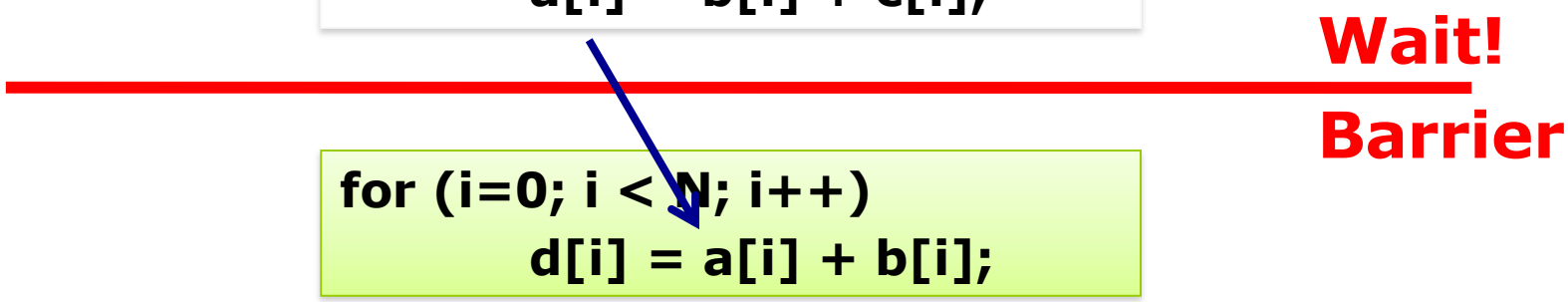
This may give us a wrong answer

Why ?

Barrier (Cont'd)

We need to have updated all of a[ ] first, before using a[ ]

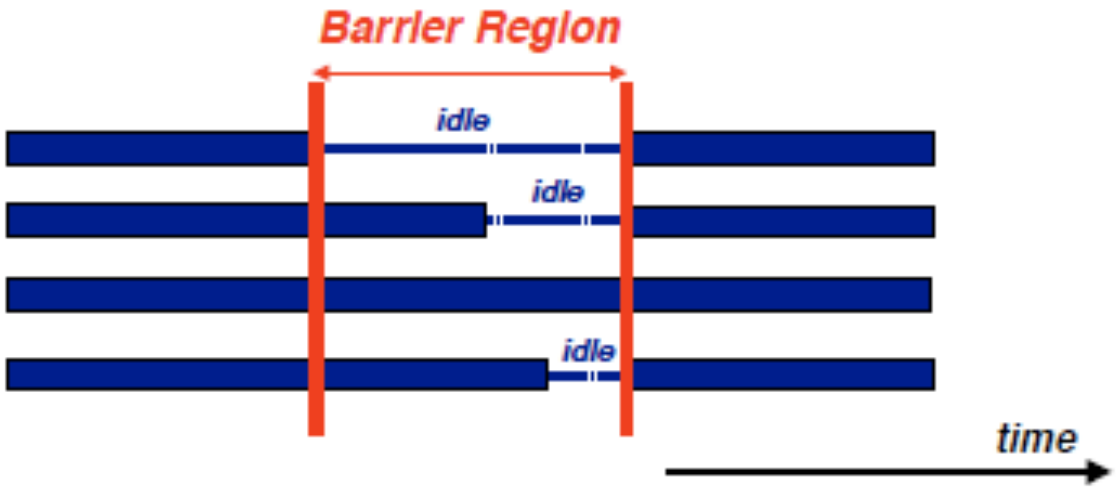
```
for (i=0; i < N; i++)
        a[i] = b[i] + c[i];
```




```
for (i=0; i < N; i++)
        d[i] = a[i] + b[i];
```

All threads wait at the barrier point and only continue when all threads have reached the barrier point

Barrier (Cont'd)



#pragma omp barrier

When to use barriers ?

- When data is updated asynchronously and the data integrity is at risk
  - Examples:
    - Between parts in the code that read and write the same section of memory
    - After one timestep/iteration in a solver
- Unfortunately, barriers tend to be expensive and also may not scale to a large number of processors
- Therefore, use them with care

The Parallel Region

- A parallel region is a block of code executed by multiple threads simultaneously

```
#pragma omp parallel [clause[[,] clause] ...]
{

        "this is executed in parallel”

} (implied barrier)
```

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 #1

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

Dependence on i

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

- Too many forks and joins

Performance improvement #1

- Invert loop

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

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

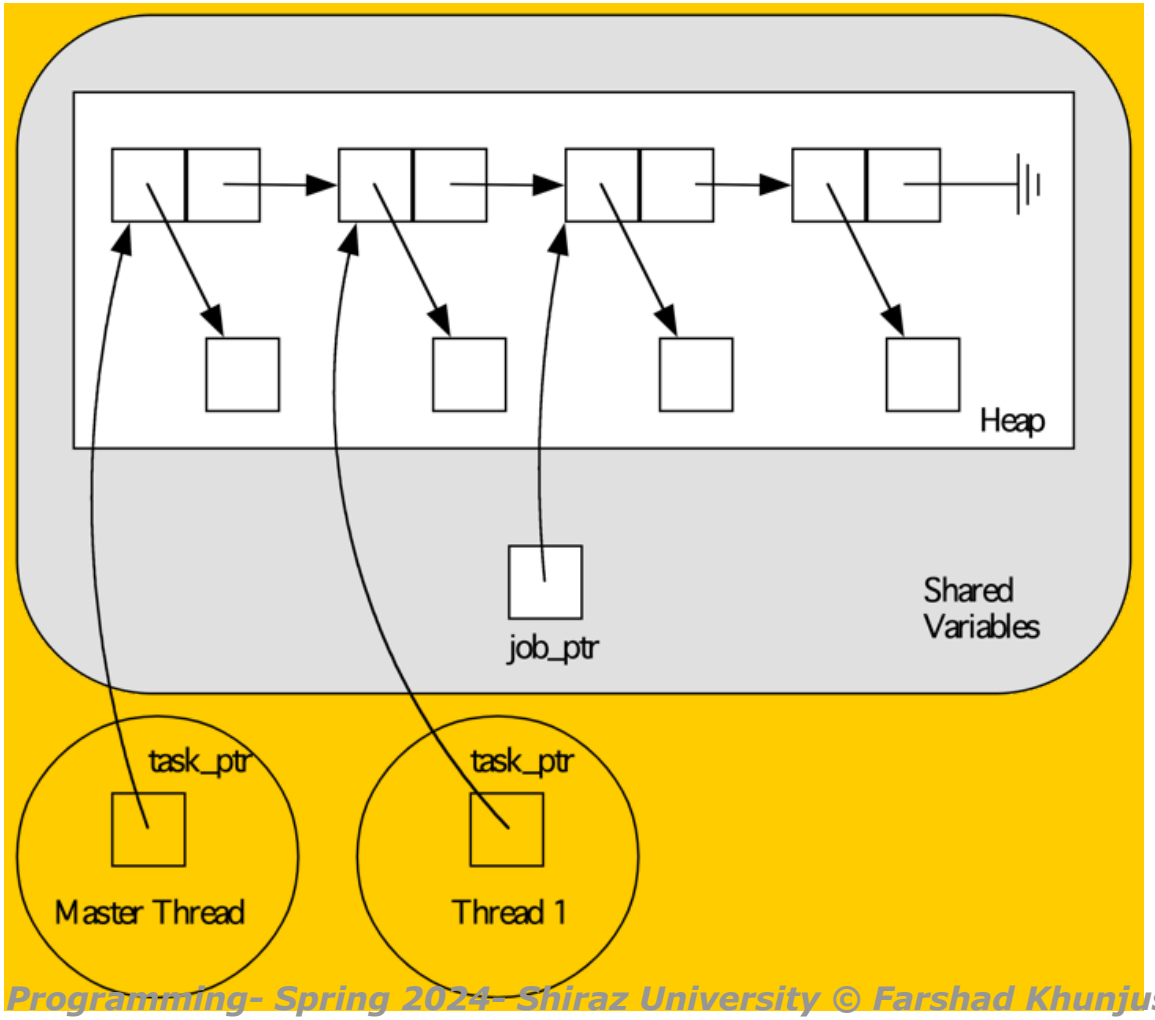
Scheduling Options (cont.)

- schedule(guided, C): dynamic allocation of chunks to tasks using guided self-scheduling heuristic. Initial chunks are bigger, later chunks are exponentially 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];
}
```

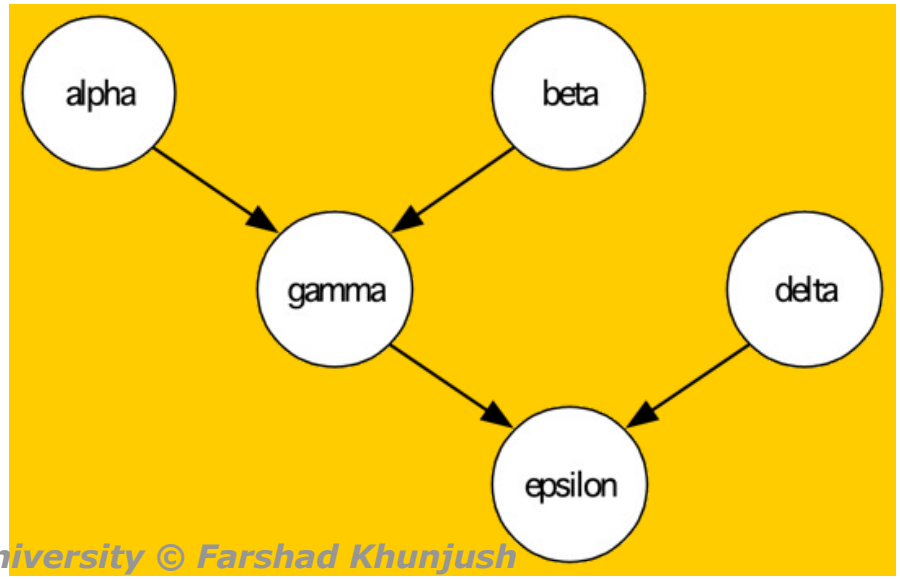
Functional Parallelism

- 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

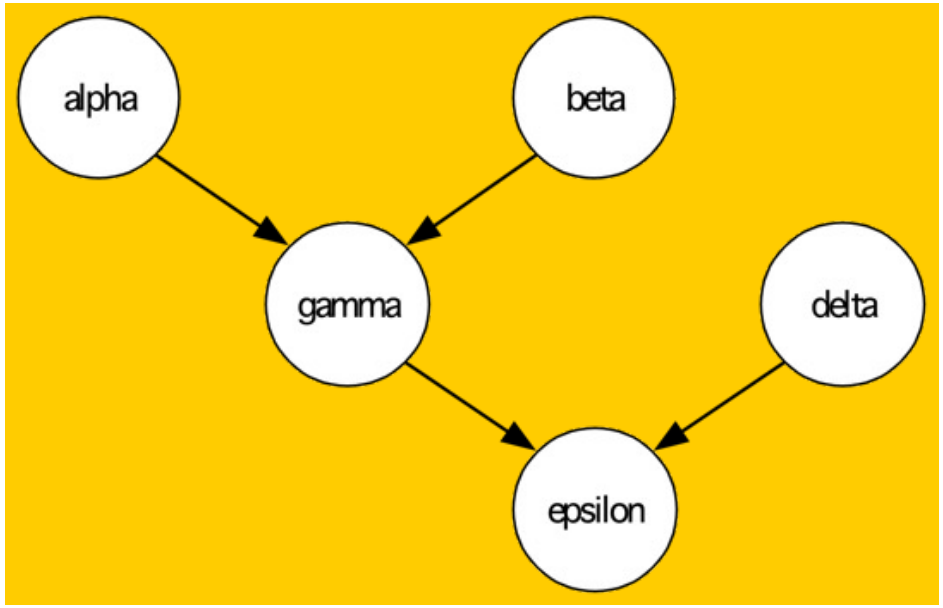
- Precedes each block of code within the encompassing block preceded by the parallel sections pragma
- May be omitted for first parallel section after the parallel sections pragma
- Syntax:

```
#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