
Programming Shared-memory Platforms with OpenMP

John Mellor-Crummey

**Department of Computer Science
Rice University**

johnmc@rice.edu

Topics for Today

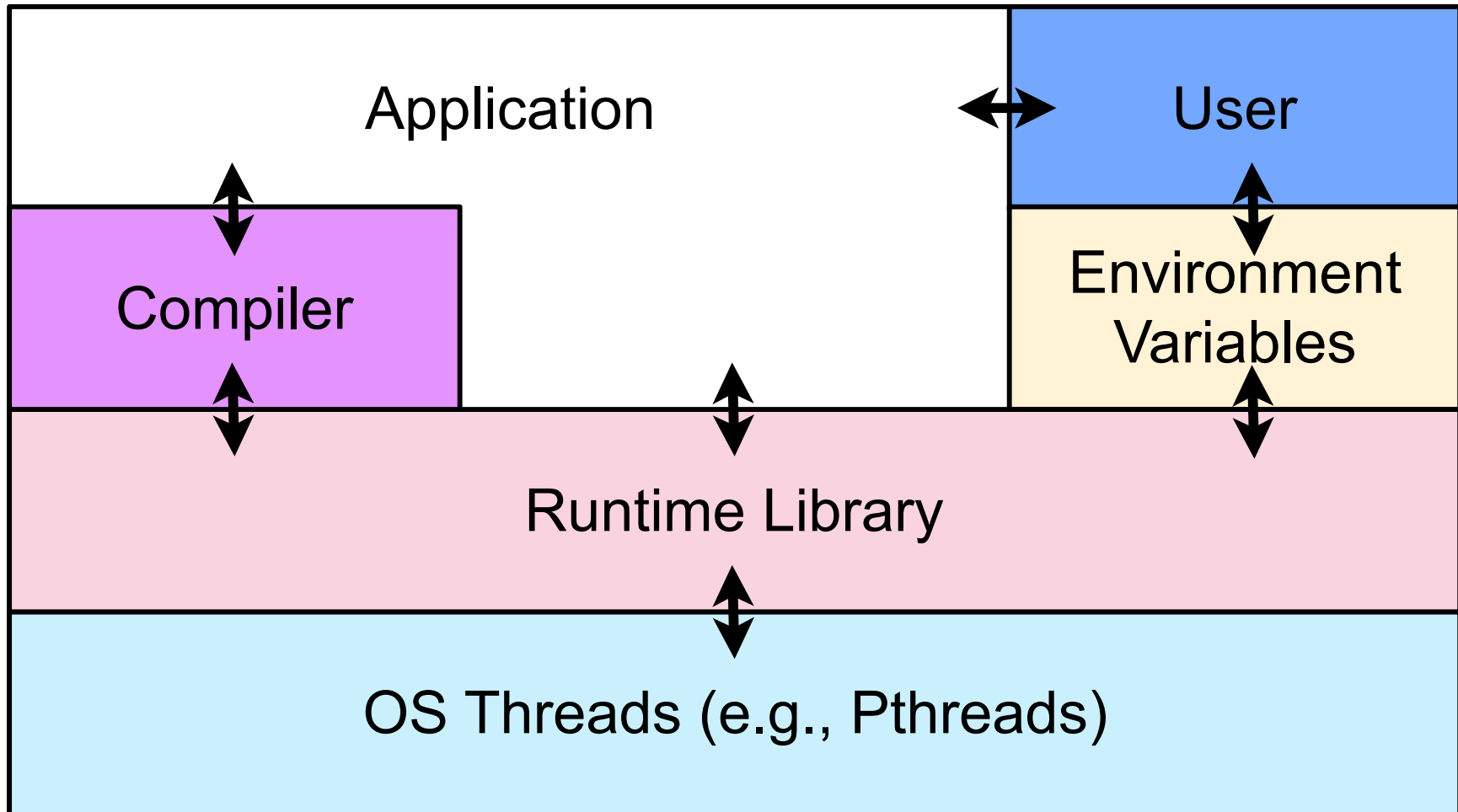
- Introduction to OpenMP
- OpenMP directives
 - concurrency directives
 - parallel regions
 - loops, sections, tasks
 - synchronization directives
 - reductions, barrier, critical, ordered
 - data handling clauses
 - shared, private, firstprivate, lastprivate
 - tasks
- Performance tuning hints
- Library primitives
- Environment variables

What is OpenMP?

Open specifications for **M**ulti **P**rocessing

- An API for explicit multi-threaded, shared memory parallelism
- Three components
 - compiler directives
 - runtime library routines
 - environment variables
- Higher-level than library-based programming models
 - implicit mapping and load balancing of work
- Portable
 - API is specified for C/C++ and Fortran
 - implementations on almost all platforms
- Standard

OpenMP at a Glance



OpenMP Is **Not**

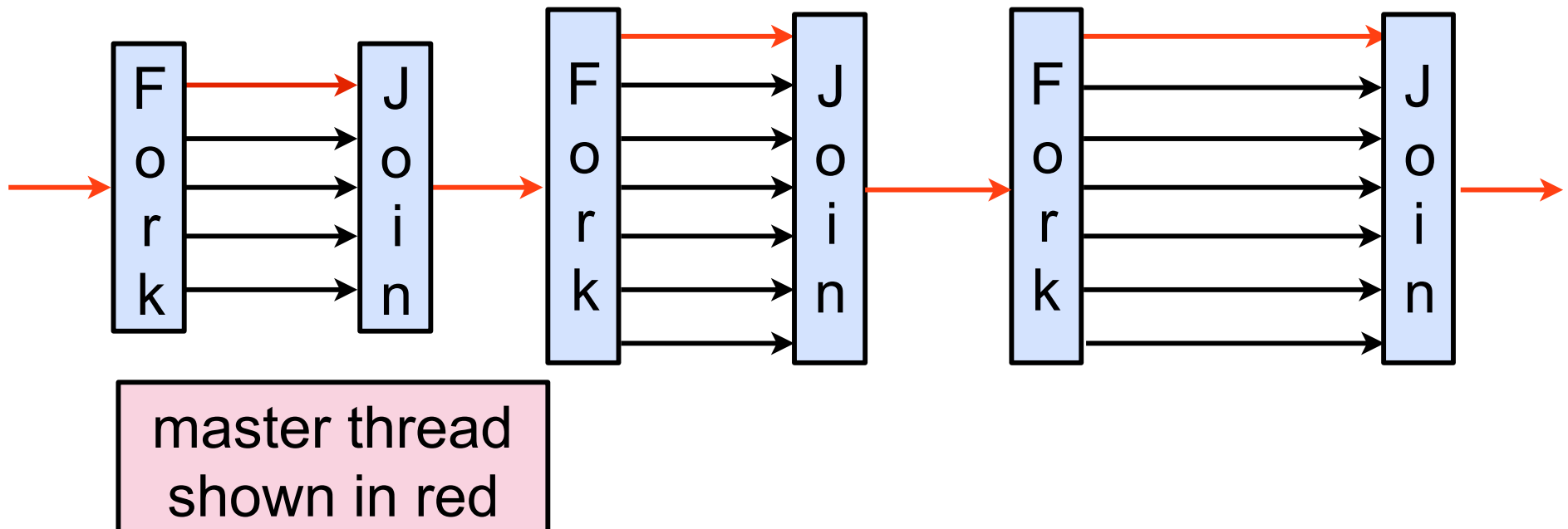
- **An automatic parallel programming model**
 - parallelism is explicit
 - programmer has full control (and responsibility) over parallelization
- **Meant for distributed-memory parallel systems (by itself)**
 - designed for shared address space machines
- **Necessarily implemented identically by all vendors**
- **Guaranteed to make the most efficient use of the memory hierarchy**

OpenMP Targets Ease of Use

- **OpenMP does not require that single-threaded code be changed for threading**
 - enables incremental parallelization of a serial program
- **OpenMP relies primarily on compiler directives**
 - pragmas (C/C++); significant comments in Fortran
 - if a compiler does not recognize a directive, it ignores it
 - significant parallelism possible using just 3 or 4 directives
 - both coarse-grain and fine-grain parallelism
- **If the compiler is not instructed to process OpenMP directives, the program will execute sequentially**
- **Runtime routines have default implementations if a compiler is not instructed to process OpenMP directives**

OpenMP: Fork-Join Parallelism

- An OpenMP program begins execution as a single master thread
- Master thread executes sequentially until 1st parallel region
- When a parallel region is encountered, master thread
 - creates a group of threads
 - becomes the master of this group of threads
 - is assigned the thread id 0 within the group



OpenMP Directive Format

- OpenMP directive forms
 - C and C++ use compiler directives
 - prefix: `#pragma ...`
 - Fortran uses significant comments
 - prefixes: `!$omp`, `c$omp`, `*$omp`
- Components: **prefix**, **directive**, **optional clauses**
 - C: `#pragma omp parallel num_threads(4)...`
 - Fortran: `!$omp parallel num_threads(4)...`

A Simple Example Using `parallel`

Program

```
#include <stdio.h>
#include <omp.h>

int main() {
    #pragma omp parallel num_threads(4)
    {
        int i = omp_get_thread_num();
        printf("Hello from thread %d\n", i);
    }
}
```

Output

```
Hello from thread 0
Hello from thread 1
Hello from thread 2
Hello from thread 3
```

order of output may vary!

OpenMP `parallel` Region Directive

```
#pragma omp parallel [clause list]
```

Typical clauses in [clause list]

- **Conditional parallelization**
 - `if (scalar expression)`
 - determines whether the `parallel` construct creates threads
- **Degree of concurrency**
 - `num_threads (integer expression) : max # threads to create`
- **Data Scoping**
 - `private (variable list)`
 - specifies variables local to each thread
 - `firstprivate (variable list)`
 - similar to `private`
 - private variables are initialized to variable value before the parallel directive
 - `shared (variable list)`
 - specifies that variables are shared among all threads in the region
 - `default (data scoping specifier)`
 - default data scoping specifier may be `shared` or `none`

A few more clauses
on slide 38

Interpreting an OpenMP Parallel Directive

```
#pragma omp parallel if (n > LARGE) num_threads(k + 1) \  
  shared(b) private(a) firstprivate(c) default(none)  
{  
  /* structured block */  
}
```

Meaning

- **if (n > LARGE)**
—if $n > \text{LARGE}$, the parallel region should create threads
- **num_threads(k + 1)**
—the value $k + 1$ is the number of threads requested
- **shared(b)**
—each thread shares a single copy of variable b
- **private(a) firstprivate(c)**
—each thread gets private copies of variables a and c
—each private copy of c is initialized with the value of c in the “initial thread” (the thread that encounters the parallel directive)
- **default(none)**
—default state of a variable is specified as **none** (rather than **shared**)
—signals error if not all variables are specified as **shared** or **private**

Specifying Worksharing

Within the scope of a parallel directive, a worksharing directive indicates that threads should cooperatively execute statements, blocks, iterations or tasks

OpenMP provides four directives

- **do/for**: threads cooperatively execute loop iterations
- **sections**: threads cooperatively execute tasks
- **single**: one arbitrary thread executes the code; others wait
- **workshare**: partitions execution of statements in a block

Worksharing **DO/for** Directive

for directive partitions parallel iterations across threads

do is the analogous directive for Fortran

- Usage:

```
#pragma omp for [clause list]
```

```
/* for loop */
```

- Possible clauses in [clause list]

- **private, firstprivate, lastprivate**

- **reduction**

- **schedule, nowait, and ordered**

- Implicit barrier at end of **for** loop

A Simple Example Using `parallel` and `for`

Program

```
void main() {  
#pragma omp parallel num_threads(3)  
{  
    int i;  
    printf("Hello world\n");  
    #pragma omp for  
    for (i = 1; i <= 4; i++) {  
        printf("Iteration %d\n", i);  
    }  
    printf("Goodbye world\n");  
}  
}
```

Output

```
Hello world  
Hello world  
Hello world  
Iteration 1  
Iteration 2  
Iteration 3  
Iteration 4  
Goodbye world  
Goodbye world  
Goodbye world
```

Reduction Clause for Parallel Directive

Specifies how to combine local copies of a variable in different threads into a single copy at the master when threads exit

- Usage: **reduction** (operator: variable list)
 - variables in list are implicitly private to threads
- Reduction operators: **+**, *****, **-**, **&**, **|**, **^**, **&&**, and **||**

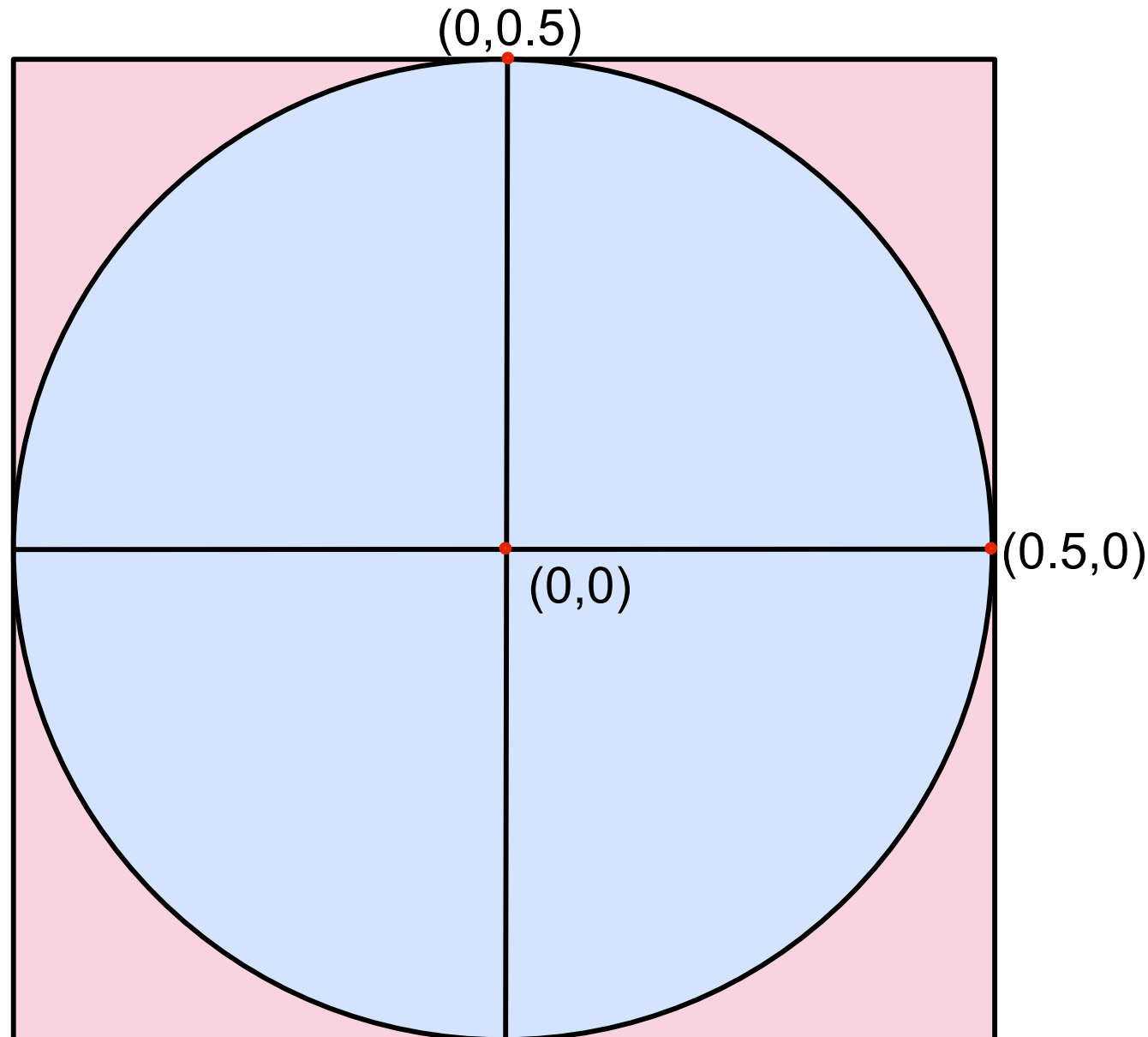
- Usage sketch

```
#pragma omp parallel reduction(+: sum) num_threads(8)
{
/* compute local sum in each thread here */
}
/* sum here contains sum of all local instances of sum */
```

Running Example: Monte Carlo Estimation of Pi

Approximate Pi

- generate random points with $x, y \in [-0.5, 0.5]$
- test if point inside the circle, i.e.,
 $x^2 + y^2 < (0.5)^2$
- ratio of circle to square =
 $\pi r^2 / 4r^2 = \pi / 4$
- $\pi \approx 4 * (\text{number of points inside the circle}) / (\text{number of points total})$



OpenMP Reduction Clause Example

OpenMP threaded program to estimate Pi

```
#pragma omp parallel default(private) shared (npoints) \  
reduction(+: sum) num_threads(8)
```

```
{
```

```
num_threads = omp_get_num_threads();  
sample_points_per_thread = npoints / num_threads;
```

```
sum = 0; seed = 17 * omp_get_thread_num();
```

```
for (i = 0; i < sample_points_per_thread; i++) {
```

```
    coord_x = (double)(rand_r(&seed)) / (double)(RAND_MAX) - 0.5;
```

```
    coord_y = (double)(rand_r(&seed)) / (double)(RAND_MAX) - 0.5;
```

```
    if ((coord_x * coord_x + coord_y * coord_y) < 0.25)
```

```
        sum++;
```

```
}
```

```
}
```

- a local copy of sum for each thread
- all local copies of sum added together and stored in master

here, user
manually
divides work

Using Worksharing **for** Directive

```
#pragma omp parallel default(private) shared (npoints) \  
    reduction(+: sum) num_threads(8)  
{  
    sum = 0;  
    seed = 17 * omp_get_thread_num();  
    #pragma omp for  
    for (i = 0; i < npoints; i++) {  
        rand_no_x =(double)(rand_r(&seed))/(double)(RAND_MAX);  
        rand_no_y =(double)(rand_r(&seed))/(double)(RAND_MAX);  
        if (((rand_no_x - 0.5) * (rand_no_x - 0.5) +  
            (rand_no_y - 0.5) * (rand_no_y - 0.5)) < 0.25)  
            sum ++;  
    }  
}
```

worksharing **for divides work**

Implicit barrier at end of loop

Mapping Iterations to Threads

schedule clause of the **for** directive

- Recipe for mapping iterations to threads
- Usage: **schedule**(**scheduling_class** [, **chunk**]).
- Four scheduling classes
 - **static**: work partitioned at compile time
 - iterations statically divided into pieces of size *chunk*
 - statically assigned to threads
 - **dynamic**: work evenly partitioned at run time
 - iterations are divided into pieces of size *chunk*
 - chunks dynamically scheduled among the threads
 - when a thread finishes one chunk, it is dynamically assigned another
 - default chunk size is 1
 - **guided**: guided self-scheduling
 - chunk size is exponentially reduced with each dispatched piece of work
 - the default minimum chunk size is 1
 - **runtime**:
 - scheduling decision from environment variable `OMP_SCHEDULE`
 - illegal to specify a chunk size for this clause.

Statically Mapping Iterations to Threads

```
/* static scheduling of matrix multiplication loops */
#pragma omp parallel default(private) \
    shared (a, b, c, dim) num_threads(4)
#pragma omp for schedule(static)
for (i = 0; i < dim; i++) {
    for (j = 0; j < dim; j++) {
        c(i,j) = 0;
        for (k = 0; k < dim; k++) {
            c(i,j) += a(i, k) * b(k, j);
        }
    }
}
```

**static schedule maps iterations
to threads at compile time**

Avoiding Unwanted Synchronization

- Default: worksharing **for** loops end with an implicit barrier
- Often, less synchronization is appropriate
 - series of independent **for**-directives within a parallel construct
- **nowait** clause
 - modifies a **for** directive
 - avoids implicit barrier at end of for

Avoiding Synchronization with **nowait**

```
#pragma omp parallel
{
    #pragma omp for nowait
        for (i = 0; i < nmax; i++)
            a[i] = ...;

    #pragma omp for
        for (i = 0; i < mmax; i++)
            b[i] = ... anything but a ...;
}
```

any thread can begin second loop immediately without waiting for other threads to finish first loop

Worksharing **sections** Directive

sections directive enables specification of task parallelism

- Usage

```
#pragma omp sections [clause list]
```

```
{
```

```
  [#pragma omp section
```

```
    /* structured block */
```

```
  ]
```

```
  [#pragma omp section
```

```
    /* structured block */
```

```
  ]
```

```
  ...
```

```
}
```



brackets here represent that
section is optional,
not the syntax for using them

Using the **sections** Directive

```
#pragma omp parallel
```

parallel section encloses all parallel work

```
{
```

```
  #pragma omp sections
```

sections: task parallelism

```
{
```

```
  #pragma omp section
```

```
{
```

```
    taskA();
```

```
}
```

```
  #pragma omp section
```

```
{
```

```
    taskB();
```

```
}
```

```
  #pragma omp section
```

```
{
```

```
    taskC();
```

```
}
```

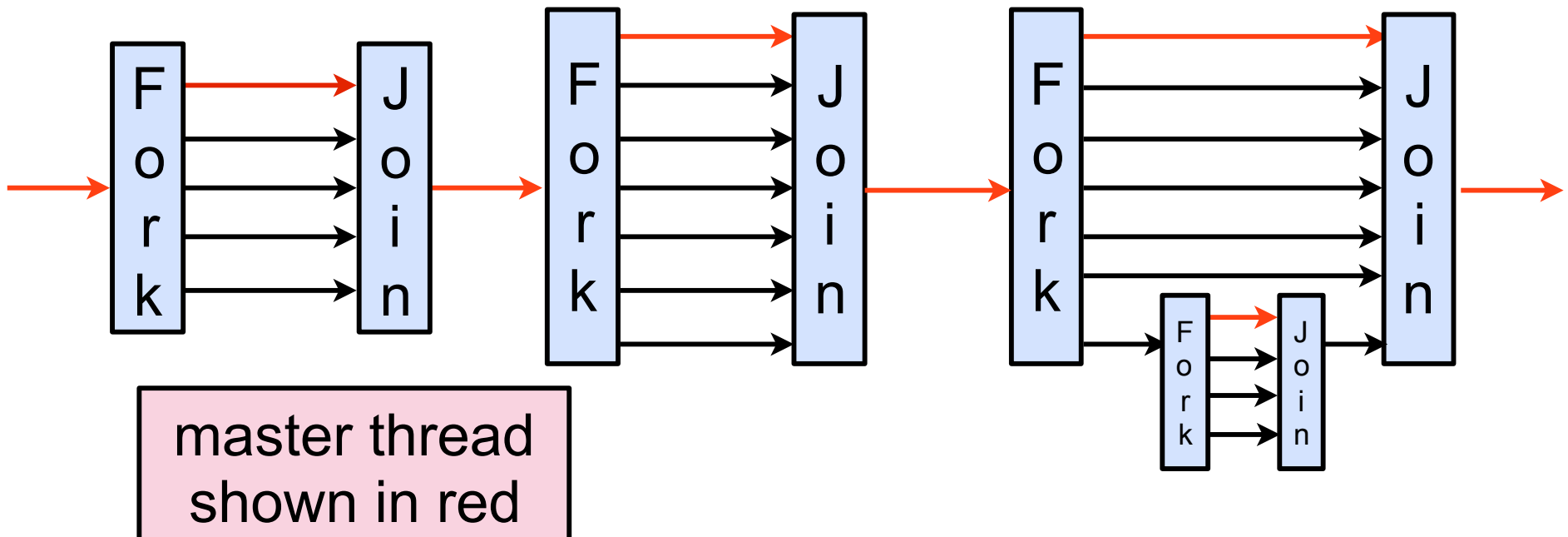
```
}
```

```
}
```

three concurrent tasks;
tasks need not
be procedure calls

Nesting **parallel** Directives

- Nested parallelism enabled using the **OMP_NESTED** environment variable
 - **OMP_NESTED = TRUE** → nested parallelism is enabled
- Each parallel directive creates a new team of threads

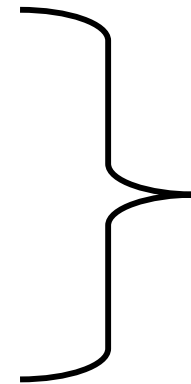


Synchronization Constructs in OpenMP

#pragma omp barrier wait until all threads arrive here

#pragma omp single [clause list]
structured block

#pragma omp master
structured block



single-threaded
execution

Use MASTER instead of SINGLE wherever possible

- **MASTER = IF-statement with no implicit BARRIER**
 - equivalent to
`IF(omp_get_thread_num() == 0) {...}`
- **SINGLE: implemented like other worksharing constructs**
 - keeping track of which thread reached SINGLE first adds overhead


Synchronization Constructs in OpenMP

#pragma omp critical [(name)] critical section: like a named lock
structured block

#pragma omp ordered for loops with carried dependences
structured block

Example Using **critical**

```
#pragma omp parallel
{
#pragma omp for nowait shared(best_cost)
  for (i = 0; i < nmax; i++) {
    my_cost = ...;
    ...
#pragma omp critical
  {
    if (best_cost < my_cost)
      best_cost = my_cost;
  }
  ...
}
}
```



**critical ensures mutual exclusion
when accessing shared state**

Example Using **ordered**

```
#pragma omp parallel  
{  
#pragma omp for nowait shared(a)  
  for (k = 0; k < nmax; k++) {  
    ...  
#pragma omp ordered  
{  
  a[k] = a[k-1] + ...;  
}  
  ...  
}  
}
```



**ordered ensures carried dependence
does not cause a data race**

Orphaned Directives

- Directives may not be lexically nested in a parallel region
 - may occur in a separate program unit

```
...  
!$omp parallel  
call phase1  
call phase2  
!$omp end parallel  
...
```

```
subroutine phase1  
!$omp do private(i) shared(n)  
do i = 1, n  
call some_work(i)  
end do  
!$omp end do  
end
```

```
subroutine phase2  
!$omp do private(j) shared(n)  
do j = 1, n  
call more_work(j)  
end do  
!$omp end do  
end
```

- Dynamically bind to enclosing parallel region at run time
- Benefits
 - enables parallelism to be added with a minimum of restructuring
 - improves performance: enables single parallel region to bind with worksharing constructs in multiple called routines
- Execution rules
 - an orphaned worksharing construct is executed serially when not called from within a parallel region

OpenMP 3.0 Tasks

- **Motivation: support parallelization of irregular problems**
 - unbounded loops
 - recursive algorithms
 - producer consumer
- **What is a task?**
 - **work unit**
 - execution can begin immediately, or be deferred
 - **components of a task**
 - code to execute, data environment, internal control variables
- **Task execution**
 - data environment is constructed at creation
 - tasks are executed by threads of a team
 - a task can be tied to a thread (i.e. migration/stealing not allowed)
 - by default: a task is tied to the first thread that executes it

OpenMP 3.0 Tasks

`#pragma omp task [clause list]`

Possible clauses in [clause list]

- Conditional parallelization
 - `if` (scalar expression)
 - determines whether the construct creates a task
- Binding to threads
 - `untied`
- Data scoping
 - `private` (variable list)
 - specifies variables local to the child task
 - `firstprivate` (variable list)
 - similar to the private
 - private variables are initialized to value in parent task before the directive
 - `shared` (variable list)
 - specifies that variables are shared with the parent task
 - `default` (data handling specifier)
 - default data handling specifier may be `shared` or `none`

Composing Tasks and Regions

```
#pragma omp parallel
```

```
{
```

```
#pragma omp task
```

```
    x();
```

```
#pragma omp barrier
```

```
#pragma omp single
```

```
{
```

```
#pragma omp task
```

```
    y();
```

```
}
```

```
}
```

```
•
```

one x task created for each thread in the parallel region

all x tasks complete at barrier

one y task created

region end: y task completes

Data Scoping for Tasks is Tricky

If no default clause specified

- Static and global variables are **shared**
- Automatic (local) variables are **private**
- Variables for orphaned tasks are **firstprivate** by default
- Variables for non-orphaned tasks inherit the shared attribute
 - task variables are **firstprivate** unless **shared** in the enclosing context

Fibonacci using OpenMP 3.0 Tasks

```
int fib ( int n )
{
    int x,y;
    if ( n < 2 ) return n;
    #pragma omp task shared(x)
    x = fib(n - 1);
    #pragma omp task shared(y)
    y = fib(n - 2);
    #pragma omp taskwait
    return x + y;
}
```

```
int main (int argc, char **argv)
{
    int n, result;
    n = atoi(argv[1]);
    #pragma omp parallel
    {
        #pragma omp single
        {
            result = fib(n);
        }
    }
    printf("fib(%d) = %d\n",
        n, result);
}
```

need **shared** for x and y;
default would be
firstprivate

suspend parent task until
children finish

create team
of threads to
execute tasks

only one thread
performs the
outermost call

List Traversal

```
Element first, e;  
#pragma omp parallel  
#pragma omp single  
{  
    for (e = first; e; e = e->next)  
#pragma omp task firstprivate(e)  
        process(e);  
}
```

Is the use of variables safe as written?

Task Scheduling

- **Tied tasks**

- only the thread that the task is tied to may execute it
- task can only be suspended at a suspend point
 - task creation
 - task finish
 - taskwait
 - barrier
- if a task is not suspended at a barrier, it can only switch to a descendant of any task tied to the thread

- **Untied tasks**

- no scheduling restrictions
 - can suspend at any point
 - can switch to any task
- implementation may schedule for locality and/or load balance

Summary of Clause Applicability

Clause	Directive					
	PARALLEL	DO/for	SECTIONS	SINGLE	PARALLEL DO/for	PARALLEL SECTIONS
IF	●				●	●
PRIVATE	●	●	●	●	●	●
SHARED	●	●			●	●
DEFAULT	●				●	●
FIRSTPRIVATE	●	●	●	●	●	●
LASTPRIVATE		●	●		●	●
REDUCTION	●	●	●		●	●
COPYIN	●				●	●
SCHEDULE		●			●	
ORDERED		●			●	
NOWAIT		●	●	●		

Performance Tuning Hints

Parallelize at the highest level, e.g. outermost **DO/for** loops

```
!$OMP PARALLEL
....
do j = 1, 20000
!$OMP DO
  do k = 1, 10000
  ...
  enddo !k
!$OMP END DO
enddo !j
....
!$OMP END PARALLEL
```

Slower

```
!$OMP PARALLEL
....
!$OMP DO
do k = 1, 10000
  do j = 1, 20000
  ...
  enddo !j
enddo !k
!$OMP END DO
....
!$OMP END PARALLEL
```

Faster

Performance Tuning Hints

Merge independent parallel loops when possible

```
!$OMP PARALLEL
.....
!$OMP DO
  statement 1
!$OMP END DO
!$OMP DO
  statement 2
!$OMP END DO
.....
!$OMP END PARALLEL
```

Slower

```
!$OMP PARALLEL
.....
!$OMP DO
  statement 1
  statement 2
!$OMP END DO
.....
!$OMP END PARALLEL
```

Faster

Performance Tuning Hints

Minimize use of synchronization

- **BARRIER**
- **CRITICAL** sections
 - if necessary, use named **CRITICAL** for fine-grained locking
- **ORDERED** regions
- Use **NOWAIT** clause to avoid unnecessary barriers
 - adding **NOWAIT** to a region's final **DO** eliminates a redundant barrier
- Use explicit **FLUSH** with care
 - flushes can evict cached values
 - subsequent data accesses may require reloads from memory

```
data = ...  
#pragma omp flush (data)  
data_available = true;
```

OpenMP Library Functions

- **Processor count**

```
int omp_get_num_procs(); /* # processors currently available */
```

```
int omp_in_parallel(); /* determine whether running in parallel */
```

- **Thread count and identity**

```
/* max # threads for next parallel region. only call in serial region */
```

```
void omp_set_num_threads(int num_threads);
```

```
int omp_get_num_threads(); /*# threads currently active */
```

```
int omp_get_max_threads(); /* max # concurrent threads */
```

```
int omp_get_thread_num(); /* thread id */
```

OpenMP Library Functions

- **Controlling and monitoring thread creation**

```
void omp_set_dynamic (int dynamic_threads);  
int  omp_get_dynamic ();  
void omp_set_nested (int nested);  
int  omp_get_nested ();
```

- **Mutual exclusion**

```
void omp_init_lock(omp_lock_t *lock);  
void omp_destroy_lock(omp_lock_t *lock);  
  
void omp_set_lock(omp_lock_t *lock);  
void omp_unset_lock(omp_lock_t *lock);  
int  omp_test_lock(omp_lock_t *lock);
```

— Lock routines have a nested lock counterpart for recursive mutexes

OpenMP Environment Variables

- **OMP_NUM_THREADS**
—specifies the default number of threads for a parallel region
- **OMP_DYNAMIC**
—specifies if the number of threads can be dynamically changed
- **OMP_NESTED**
—enables nested parallelism (may be nominal: one thread)
- **OMP_SCHEDULE**
—specifies scheduling of **for**-loops if the clause specifies runtime
- **OMP_STACKSIZE** (for non-master threads)
- **OMP_WAIT_POLICY** (active or passive)
- **OMP_MAX_ACTIVE_LEVELS**
— integer value for maximum # nested parallel regions
- **OMP_THREAD_LIMIT** (# threads for entire program)

OpenMP Directives vs. Library-based Models

- **Directive advantages**

- directives facilitate a variety of thread-related tasks
- frees programmer from
 - initializing thread attributes
 - setting up thread arguments
 - partitioning iteration spaces, ...

- **Directive disadvantages**

- data exchange is less apparent
 - leads to mysterious overheads
 - data movement, false sharing, and contention
- API is less expressive than Pthreads
 - lacks condition waits, locks of different types, and flexibility for building composite synchronization operations

OpenMP is Continuing to Evolve

- OpenMP 5.0 is the most recent standard (November 2018)
- Features new to OpenMP 4
 - SIMD support
 - e.g., `a[0:n-1] = 0`
 - locality and affinity
 - control mapping of threads to processor cores
 - `proc_bind (master, spread, close)`
 - additional synchronization mechanisms
 - e.g., `taskgroup`, `taskwait`
 - offload computation to accelerators, e.g. GPUs
- OpenMP 5.1 will be released in November 2020
 - changes include full support for C11 and C++11/14/17, extensions to support C++ attribute specifiers; `tile`, `error` and `assume` directives; iterator support for data motion clauses, the `interop` directive, extensions to task dependences, extensions to SIMD constructs and the `declare variant` directive as well as clarifications and improvements to existing features

References

- **Blaise Barney.** LLNL OpenMP tutorial. <http://www.llnl.gov/computing/tutorials/openMP>
- **Adapted from slides “Programming Shared Address Space Platforms” by Ananth Grama**
- **Ananth Grama, Anshul Gupta, George Karypis, and Vipin Kumar.** Introduction to Parallel Computing. Chapter 7. Addison Wesley, 2003.
- **Sun Microsystems.** OpenMP OpenMP API User's Guide. Chapter 7 “Performance Considerations” http://docs.sun.com/source/819-3694/7_tuning.html
- **Alberto Duran.** OpenMP 3.0: What's New?. IWOMP 2008. <http://cobweb.ecn.purdue.edu/ParaMount/iwomp2008/documents/omp30>
- **Stephen Blair-Chappell.** “Expressing Parallelism Using the Intel Compiler.” http://www.polyhedron.com/web_images/documents/Expressing%20Parallelism%20Using%20Intel%20Compiler.pdf
- **Rusty Lusk et al.** Programming Models and Runtime Systems, Exascale Software Center Meeting, ANL, Jan. 2011.
- **OpenMP 4.5 Standard,** <https://www.openmp.org/wp-content/uploads/openmp-4.5.pdf>
- **OpenMP Application Program Interface Examples.** <https://www.openmp.org/wp-content/uploads/openmp-examples-4.5.0.pdf>

References

- OpenMP 5.0 Standard, <https://www.openmp.org/wp-content/uploads/OpenMP-API-Specification-5.0.pdf>
- OpenMP TR 8. <https://www.openmp.org/wp-content/uploads/openmp-TR8.pdf>