Programming Shared-memory Platforms with OpenMP

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Topics for Today

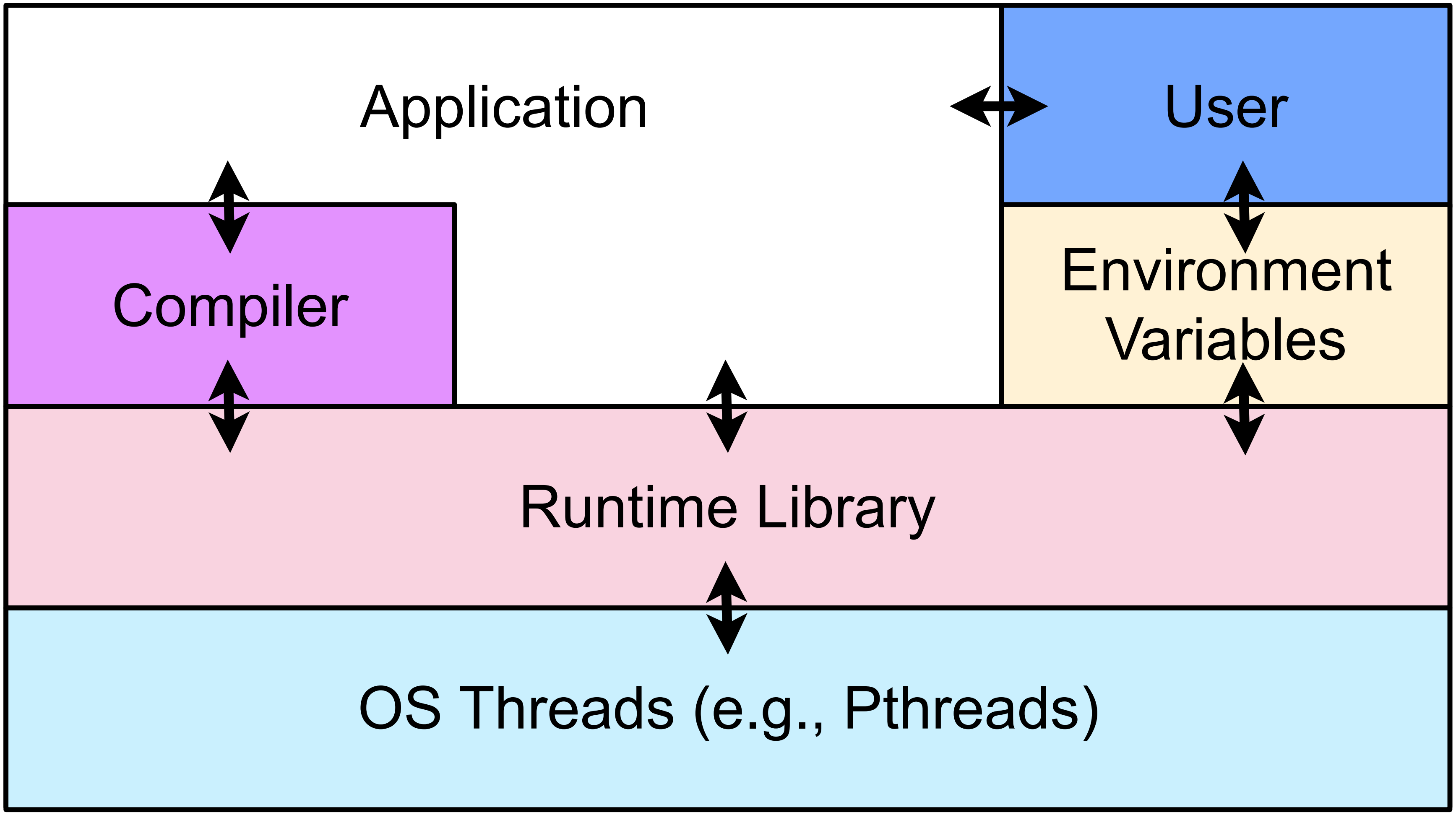
- Introduction to OpenMP
- OpenMP directives
  - concurrency directives
    - parallel regions
    - loops, sections, tasks
  - synchronization directives
    - reductions, barrier, critical, ordered
  - data handling clauses
    - shared, private, firstprivate, lastprivate
  - tasks
- Performance tuning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

What is OpenMP?

Open specifications for Multi Processing

- 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

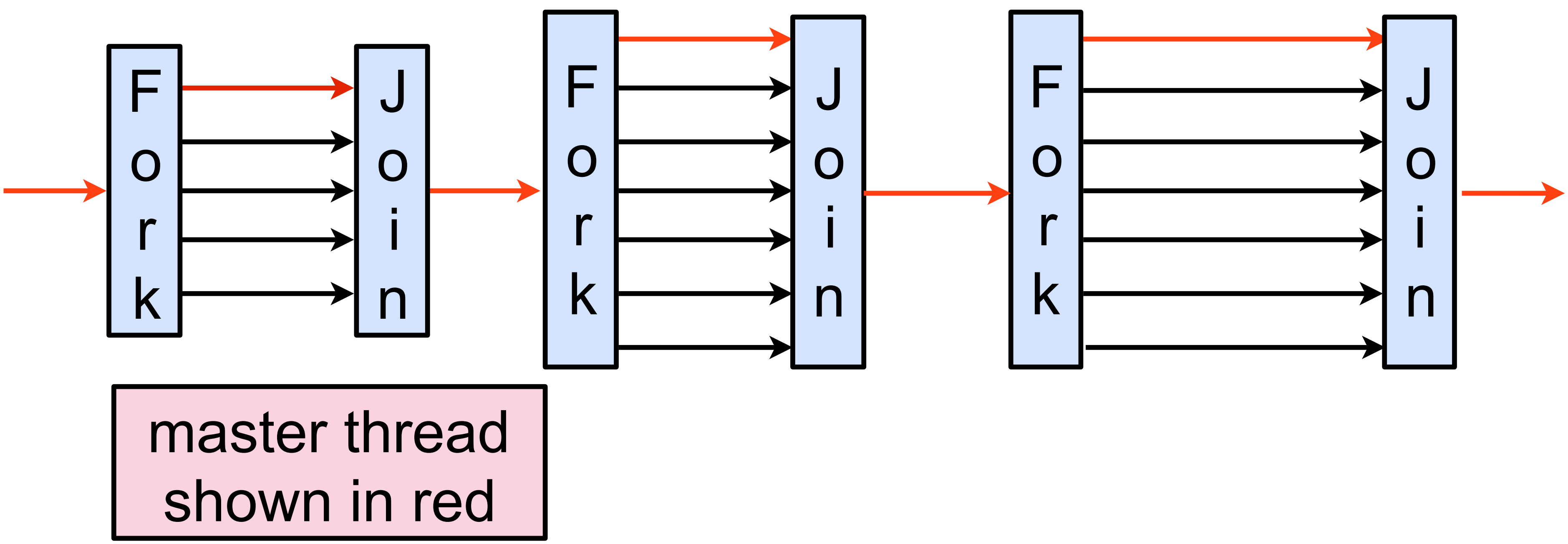
- An automatic parallel programming model
  - — parallelism is explicit
  - — programmer has full control (and responsibility) over parallelization
- Meant for distributed-memory parallel systems (by itself)
  - — designed for shared address spaced machines
- Necessarily implemented identically by all vendors
- Guaranteed to make the most efficient use of shared memory
  - — no data locality control

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 only adds compiler directives
  - pragmas (C/C++); significant comments in Fortran
    - if a compiler does not recognize a directive, it ignores it
  - simple & limited set of directives for shared memory programs
  - significant parallelism possible using just 3 or 4 directives
    - both coarse-grain and fine-grain parallelism
- If OpenMP is disabled when compiling a program, the program will execute sequentially

OpenMP: Fork-Join Parallelism

- **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, comp, *$omp
- A directive consists of a directive name followed by 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]

A few more clauses on slide 38

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 the private
    - private variables are initialized to variable value before the parallel directive
  - `shared` (variable list)
    - specifies that variables are shared across all the threads
  - `default` (data scoping specifier)
    - default data scoping specifier may be `shared` or `none`

Interpreting an OpenMP Parallel Directive

```
#pragma omp parallel if (is_parallel==1)  num_threads(8) \
  shared(b) private(a) firstprivate(c) default(none)
{
 /* structured block */
}
```

Meaning

- `if (is_parallel== 1) num_threads(8)`
  - —If the value of the variable `is_parallel` is one, create 8 threads
- `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," which is the one 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, worksharing directives allow concurrency between iterations or tasks

OpenMP provides four directives

- `DO/for`: concurrent loop iterations
- `sections`: concurrent tasks
- `workshare`: partition execution of statements in block
- `single`: one arbitrary thread executes the code

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

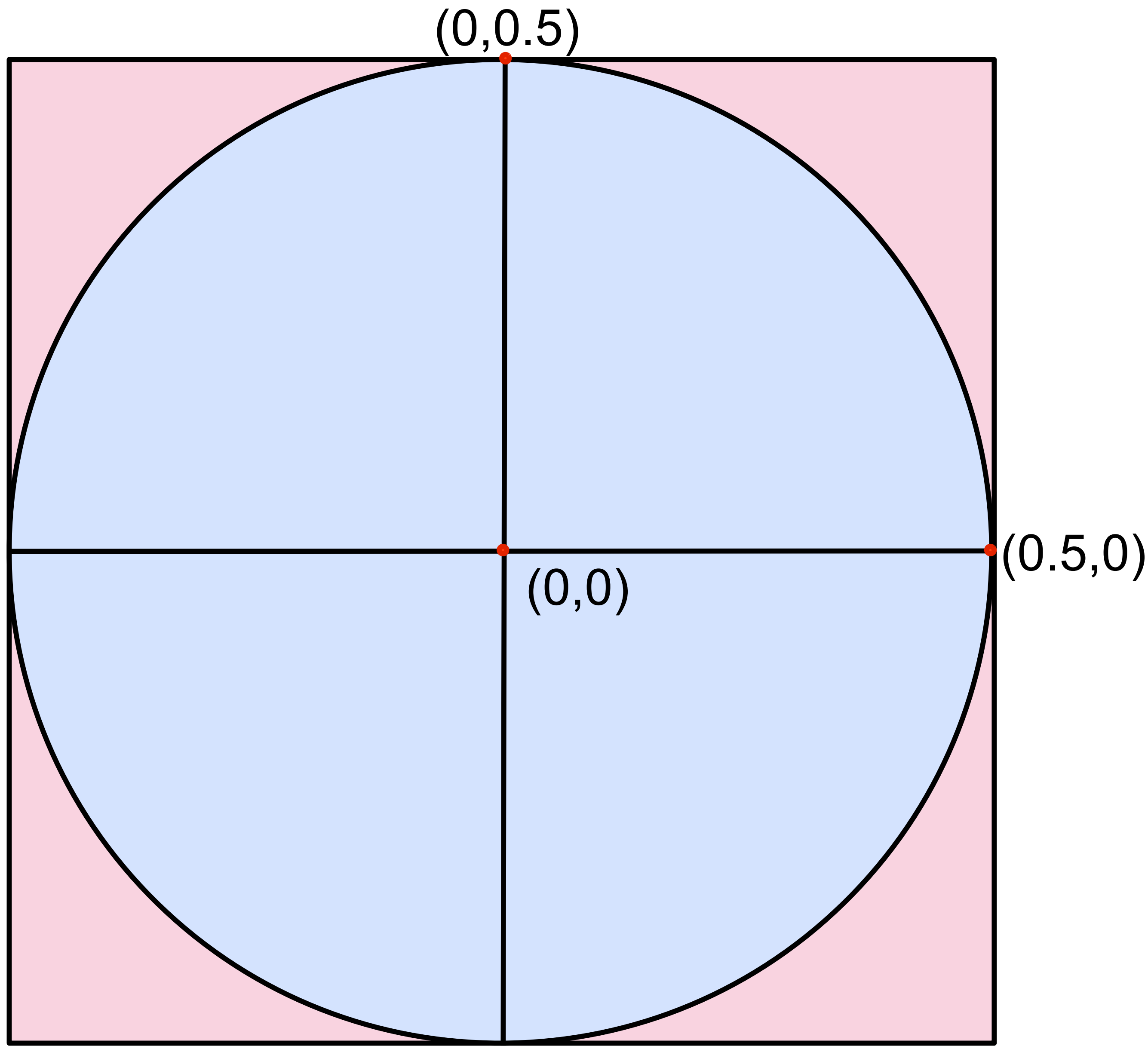
- **Usage:** `reduction` **(operator: variable list)**
  - — variables in list are implicitly private to threads
- **Reduction operators:** +, *, -, &, |, ^, &&, and ||
- **Usage sketch**

```
#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 = $\pi r^2 / 4r^2 = \pi / 4$
- $\pi \approx 4 *$ (number of points inside the circle) / (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;
    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++;
    }
}
```

here, user manually divides work

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

Using Worksharing `for` Directive

```
#pragma omp parallel default(private) shared (npoints) \
    reduction(+: sum) num_threads(8)
{
    sum = 0;
    #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
{
    #pragma omp sections
    {
      #pragma omp section
      {
          taskA();
      }
      #pragma omp section
      {
          taskB();
      }
      #pragma omp section
      {
          taskC();
      }
    }
}
```

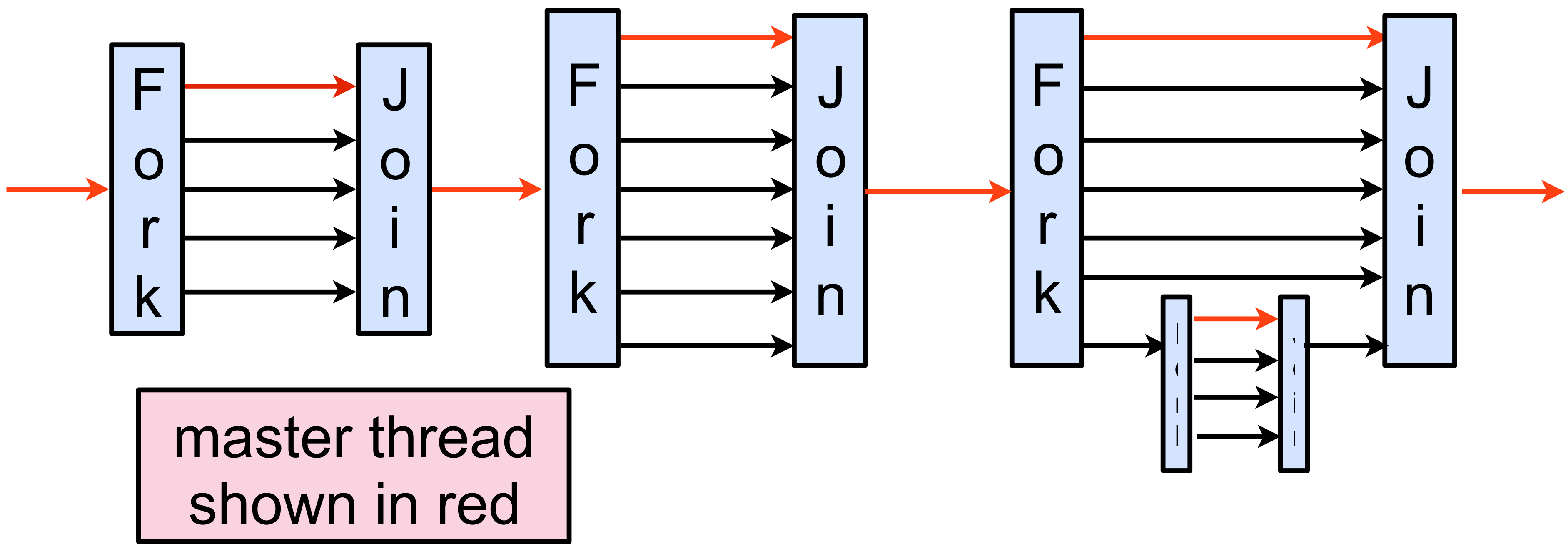
parallel section encloses all parallel work

sections: task parallelism

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)]
    structured block
```

critical section: like a named lock

```
#pragma omp ordered
    structured block
```

for loops with carried dependences

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 <u>tied</u> 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 (Power9ed) 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);
}
```

create team of threads to execute tasks

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

suspend parent task until children finish

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 */
```

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**
  - —specfies 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 attribute objects
    - 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 4.5 is the most recent standard (November 2015)
- 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
- Work in progress
  - —OpenMP Tools API (OMPT)

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