Parallel & Distributed Computing

Programming with OpenMP

Lecture 4, Spring 2014

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Overall Outline

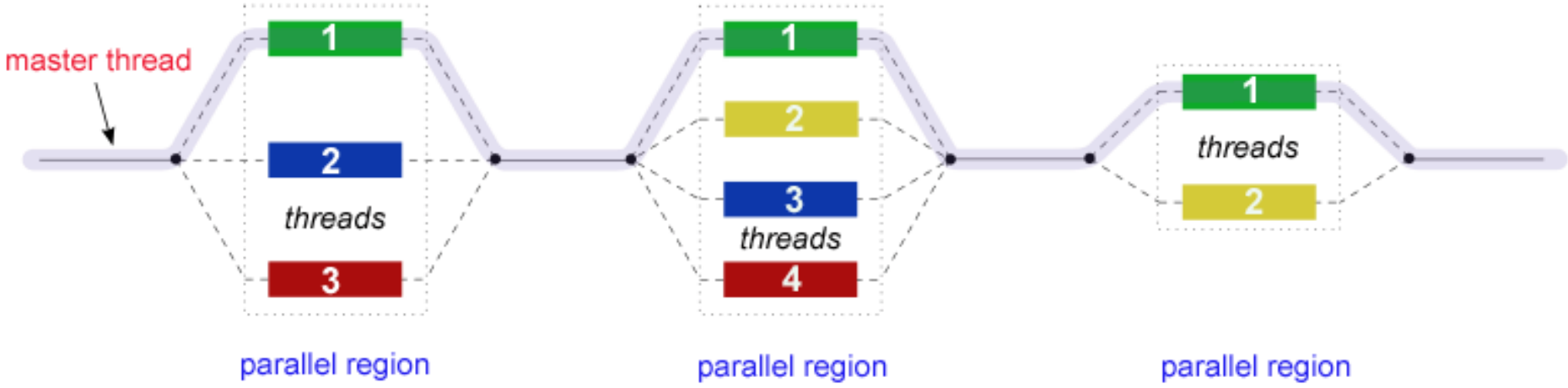
- Basics of OpenMP
  - APIs, directives, etc.
- Correctness
  - Barriers
  - Race conditions
  - Mutual Exclusion
  - Memory fence
- Performance
  - Locality
  - Loop scheduling
  - Loop transformations

What is OpenMP?

- **An abbreviation for**
  - **Short version**
    - **Open Multi-Processing**
  - **Long version**
    - **Open specifications for Multi-Processing via collaborative work between interested parties from the hardware and software industry, government and academia**
- **OpenMP is an API for parallel programming**
  - **First developed by the OpenMP Architecture Review Board (1997), now a standard**
  - **Designed for shared-memory multiprocessors**
  - **Set of compiler directives, library functions, and environment variables, but not a language**
  - **Can be used with C, C++, or Fortran**
  - **Based on fork/join model of threads**

Fork-Join Model

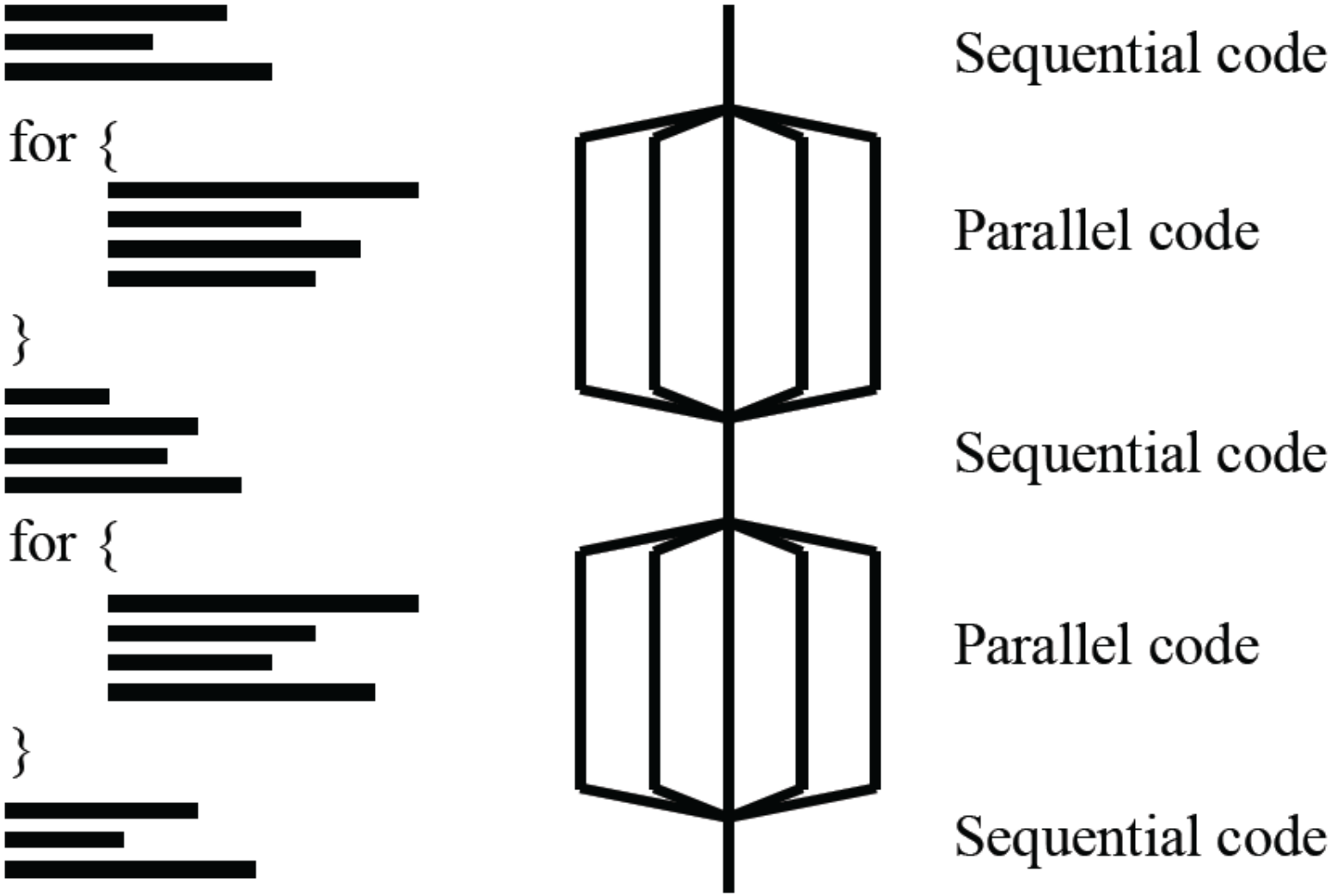
- **FORK**
  - **The master thread then creates (or awakens) a team of parallel *threads*.**
- **JOIN**
  - **When the team threads complete the statements in the parallel region construct, they synchronize and terminate, leaving only the master thread.**



http://en.wikipedia.org/wiki/Flynn's_taxonomy

Blaise Barney (LLNL), Introduction to Parallel Computing

Relating Fork/Join to Code



OpenMP Components

- **Three API components**
  - **Compiler directives**
  - **Runtime library routines**
  - **Environment variables**

http://en.wikipedia.org/wiki/Flynn's_taxonomy

Syntax of Compiler Directives

- *pragma*: a C/C++ compiler directive
  - (other compiler directives: #include, #define, …)
  - Stands for "pragmatic information"
  - A way for the programmer to communicate with the compiler
  - Pragmas are handled by the preprocessor
  - Compilers are free to ignore pragmas
- All OpenMP pragmas have the syntax:

  #pragma omp <directive-name> [clause, ...]
- Pragmas appear immediately *before* relevant construct

Hello World

```
#include <omp.h>
#include <stdio.h>
#include <stdlib.h>
int main (int argc, char *argv[]) {
  int nthreads, tid;
  /* Fork a team of threads giving them their own copies of variables */
#pragma omp parallel private(nthreads, tid)
  {
    /* Obtain thread number */
    tid = omp_get_thread_num();
    /* Only master thread does this */
    if (tid == 0) {
      nthreads = omp_get_num_threads();
      printf("Number of threads = %d\n", nthreads);
    }
    printf("Hello World from thread = %d\n", tid);
  }  /* All threads join master thread and disband */
}
```

Output – Non-deterministic!

```
[cong@lnxsrvg1 ~/cs133_examples]$ ./a.out
Hello World from thread = 5
Hello World from thread = 7
Number of threads = 16
Hello World from thread = 0
Hello World from thread = 8
Hello World from thread = 3
Hello World from thread = 1
Hello World from thread = 6
Hello World from thread = 15
Hello World from thread = 14
Hello World from thread = 10
Hello World from thread = 2
Hello World from thread = 9
Hello World from thread = 11
Hello World from thread = 13
Hello World from thread = 12
Hello World from thread = 4
[cong@lnxsrvg1 ~/cs133_examples]$ ./a.out
Hello World from thread = 6
Hello World from thread = 10
Hello World from thread = 8
Number of threads = 16
Hello World from thread = 0
Hello World from thread = 5
Hello World from thread = 14
Hello World from thread = 15
Hello World from thread = 13
Hello World from thread = 12
Hello World from thread = 4
Hello World from thread = 3
Hello World from thread = 9
Hello World from thread = 2
Hello World from thread = 7
Hello World from thread = 1
Hello World from thread = 11
```

Supplemental: printf & cout

- **C/C++ is not aware of "threads," but POSIX is.**
  - **http://pubs.opengroup.org/onlinepubs/9699919799/functions/flockfile.html**
  - **All functions that reference (FILE *) objects shall behave as if they use flockfile() and funlockfile() internally to obtain ownership of these (FILE *) objects.**
- **What about replacing the printf statement … ?**

```
printf("Hello World from thread = %d\n", tid);
```

by

```
cout << "Hello World from thread = " << tid << endl;
```

OpenMP Compilers Perform the Translations to Threads (e.g. pthreads)

```
int a, b;
main() {
  // serial segment
  #pragma omp parallel num_threads (8) private (a) shared (b)
  {
    // parallel segment
  }
  // rest of serial segment
}
```

Sample OpenMP program

```
int a, b;
main() {
  // serial segment

  for (i = 0; i < 8; i++)
    pthread_create (......., internal_thread_fn_name, ...);

  for (i = 0; i < 8; i++)
    pthread_join (.......);

  // rest of serial segment

}

void *internal_thread_fn_name (void *packaged_argument) {
  int a;

  // parallel segment

}
```

Code inserted by the OpenMP compiler

Corresponding Pthreads translation

A. Grama et al., "Introduction to Parallel Computing," Addison Wesley, 2003

Matching Threads with CPUs

- **Function *omp_get_num_procs* returens the number of physical processors available to the parallel program**

```
int omp_get_num_procs(void);
```

- **Function *omp_set_num_threads* allow you to set the number of threads that should be active in parallel sections of code**

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

  - **The function can be called with different arguments at different points in the program**

Pragma: *parallel for*

- **The compiler directive**

  #pragma omp parallel for

  tells the compiler that the *for* loop which immediately follows can be executed in parallel

  - **The number of loop iterations must be computable at run time before loop executes**
  - **Loop must not contain a *break*, *return*, or *exit***
  - **Loop must not contain a *goto* to a label outside loop**

Example: parallel for

```
int a[1000], b[1000], s[1000];
…
#pragma omp parallel for
for (i = 0; i < 1000; i ++)
    s[i] = a[i] + b[i];
```

- **Threads are assigned an independent set of iterations**
- **Threads must wait at the end of construct**

Which Loop to Make Parallel?

```
int main() {
    int i, j, k;
    float **a, **b;
    … // initialize a[][], b[][] as the 1-hop distance matrix
    for (k = 0; k < N; k++) {
        for (i = 0; i < N; i++)
            for (j = 0; j < N; j++)
                a[i][j] = min(a[i][j], b[i][k] + b[k][j]);
        … // copy a[][] to b[][]
    }
```

Which Loop to Make Parallel?

```
int main() {
    int i, j, k;
    float **a, **b;
    … // initialize b[][] as the 1-hop distance matrix
    for (k = 0; k < N; k++)          // Loop-carried dependences
        for (i = 0; i < N; i++)      // Can execute in parallel
            for (j = 0; j < N; j++)  // Can execute in parallel
                a[i][j] = min(a[i][j], b[i][k] + b[k][j]);
    … // copy a[][] to b[][]
```

Minimizing Threading Overhead

- **There is a fork/join for every instance of**

```
#pragma omp parallel for
for (…) {
    …
}
```

- **Since fork/join is a source of overhead, we want to maximize the amount of work done for each fork/join; i.e., the *grain size***
- **Hence we choose to make the middle loop parallel**

Almost Right, but Not Quite

```
int main() {
    int i, j, k;
    float **a , **b;
    … // initialize b[][] as the 1-hop distance matrix
    for (k = 0; k < N; k++) {
        #pragma omp parallel for
        for (i = 0; i < N; i++)
            for (j = 0; j < N; j++)
                a[i][j] = min(a[i][j], b[i][k] + b[k][j]);
        … // copy a[][] to b[][]
    }
```

Problem: j is a shared variable

Clause: private

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

  #pragma omp … private (<variable list>)

Problem Solved with *private* Clause

```
int main() {
    int i, j, k;
    float **a , **b;
    … // initialize b[][] as the 1-hop distance matrix
    for (k = 0; k < N; k++) {
        #pragma omp parallel for private (j)
        for (i = 0; i < N; i++)
            for (j = 0; j < N; j++)
                a[i][j] = min(a[i][j], b[i][k] + b[k][j]);
        … // copy a[][] to b[][]
    }
```

Tell compiler to make listed variables private

Another Example

```
int i;
float *a, *b, *c, tmp;
…
for (i = 0; i < N; i++) {
    tmp = a[i] / b[i];
    c[i] = tmp * tmp;
}
```

- **Loop is perfectly parallelizable except for shared variable *tmp***

Solution

```
int i;
float *a, *b, *c, tmp;
…
#pragma omp parallel for private (tmp)
for (i = 0; i < N; i++) {
      tmp = a[i] / b[i];
      c[i] = tmp * tmp;
}
```

More About Private Variables

- **Each thread has its own copy of the private variables**
- **If *j* is declared private, then inside the *for* loop no thread can access the "other" *j* (the *j* in shared memory)**
- **No thread can use a previously defined value of *j***
- **No thread can assign a new value to the shared *j***
- **Private variables are undefined at loop entry and loop exit, reducing execution time**

Clause: *firstprivate*

- **The *firstprivate* clause tells the compiler that the private variable should inherit the value of the shared variable upon loop entry**
  - **The value is assigned once per thread, not once per loop iteration**

Example: *firstprivate*

```
a[0] = 0.0;
for (i = 1; i < N; i++)
    a[i] = alpha(i, a[i-1]);

#pragma omp parallel for firstprivate (a)
for (i = 0; i < N; i++)
    b[i] = beta(i, a[i]);
    a[i] = gamma(i);
    c[i] = delta(a[i], b[i]);
}
```

Clause: *firstprivate*

- #pragma omp … firstprivate(x)
  - ***x* is a fundamental data type**
    - **Private *x* is directly copied from the shared *x***
  - ***x* is an array**
    - **Copy the data with *sizeof(x)* to the private memory**
  - ***x* is a pointer**
    - **Private *x* points to the same location as the shared *x***
  - ***x* is a class instance**
    - **Copy constructor is called to create the private *x***

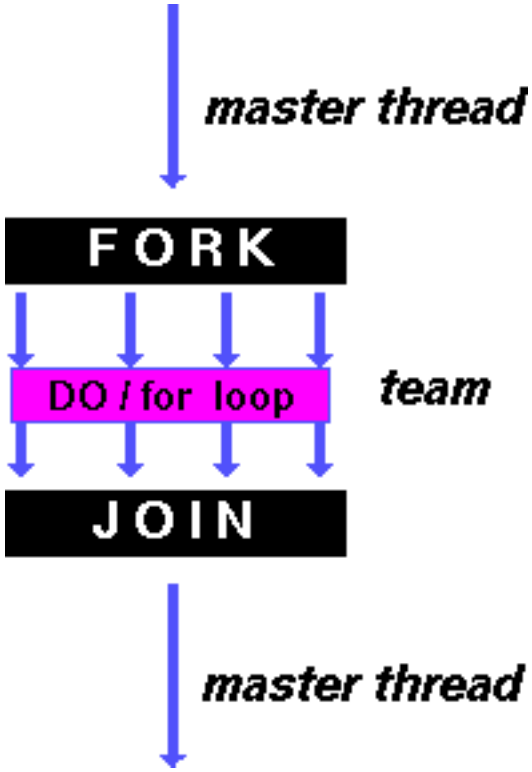
Clause: *lastprivate*

- **The *lastprivate* clause tells the compiler that the value of the private variable after the *sequentially last* loop iteration should be assigned to the shared variable upon loop exit**
  - **In other words, when the thread responsible for the sequentially last loop iteration exits the loop, its copy of the private variable is copied back to the shared variable**

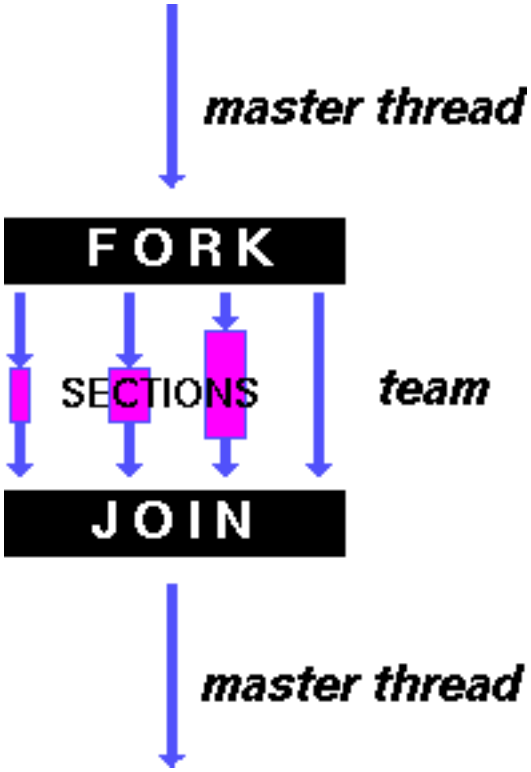
Example: lastprivate

```
#pragma omp parallel for lastprivate (x)
for (i = 0; i < N; i++)
    x = foo(i);
    y[i] = bar(i, x);
}
last_x = x; // == foo(N-1)
```

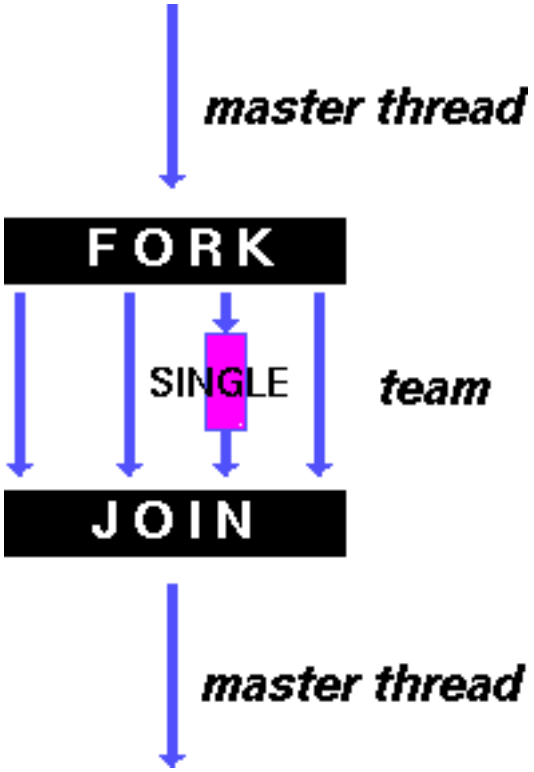
Work-Sharing Constructs



a type of "data parallelism".



a type of "functional parallelism".



serializes a section of code

Pragma: *parallel*

- **In the effort to increase grain size, sometimes the code that should be executed in parallel goes beyond a single *for* loop**
  - **The *parallel* pragma is used when a block of code should be executed in parallel**
  - **SPMD-style programming**
    - **Single program, multiple data**

Pragma: *for*

- **The *for* pragma is used inside a block of code already marked with the *parallel* pragma**
  - **It indicates a *for* loop whose iterations should be divided among the active threads**
  - **There is a *barrier synchronization* of the threads at the end of the *for* loop**

Pragma parallel ***and Pragma*** for

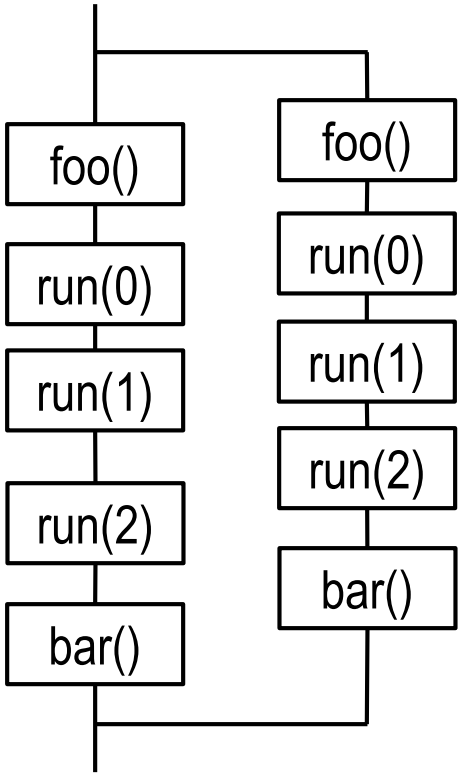
- #pragma omp for
  - **Used inside a block of code already marked by** *parallel*
  - **Distribute the iterations to the active threads**

```
#pragma omp parallel \
 num_threads(2)
{
      foo();
      #pragma omp for
      for (int i = 0; i < 3; i++)
            run(i);
      bar();
}
```

```
#pragma omp parallel \
 num_threads(2)
{
      foo();
      for (int i = 0; i < 3; i++)
            run(i);
      bar();
}
```

Pragma parallel ***and Pragma*** for

- #pragma omp for
  - **Used inside a block of code already marked by *parallel***
  - **Distribute the iterations to the active threads**

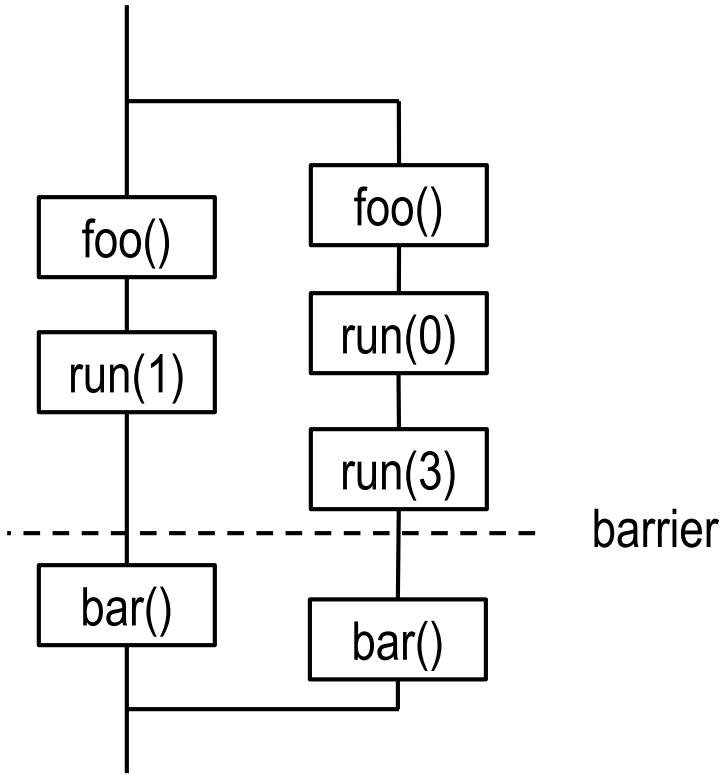



```
#pragma omp parallel \
 num_threads(2)
{
      foo();
      for (int i = 0; i < 3; i++)
            run(i);
      bar();
}
```

Pragma parallel ***and Pragma*** for

- #pragma omp for
  - **Used inside a block of code already marked by *parallel***
  - **Distribute the iterations to the active threads**

```
#pragma omp parallel \
 num_threads(2)
{
      foo();
      #pragma omp for
      for (int i = 0; i < 3; i++)
            run(i);
      bar();
}
```



Parallelize For Loop

Pragma: *single*

- **The *single* pragma is used inside a parallel block of code**
  - **It tells the compiler that only a single thread should execute the statement or block of code immediately following**
  - **May be useful when dealing with sections of code that are not thread safe (such as I/O)**
  - **Threads in the team that do not execute the** single **directive, wait at the end of the enclosed code block, unless a** nowait **clause is specified.**

Example: master and single nowait

```
tid = omp_get_thread_num();
if (tid == 0) {
      nthreads = omp_get_num_threads();
      printf("Number of threads = %d\n", nthreads);
}
```

=

```
#pragma omp master
{
      nthreads = omp_get_num_threads();
      printf("Number of threads = %d\n", nthreads);
}
```

≈

```
#pragma omp single nowait
{
      nthreads = omp_get_num_threads();
      printf("Number of threads = %d\n", nthreads);
}
```

Pragma: sections and section

- **Directive** sections **specifies that the enclosed section(s) of code are to be divided among the threads in the team.**
- **Independent section directives are nested within a** sections **directive.**
  - **Each** section **is executed once by a thread in the team.**
  - **Different sections may be executed by different threads.**
  - **It is possible for a thread to execute more than one section if it is quick enough and the implementation permits such.**

Example: sections and section

```
#pragma omp parallel shared(a,b,c,d) private(i)
{
#pragma omp sections
   {
#pragma omp section
     {
       for (i=0; i<N; i++)
         c[i] = a[i] + b[i];
     }
#pragma omp section
     {
       for (i=0; i<N; i++)
         d[i] = a[i] * b[i];
     }
   }  /* end of sections */
 }  /* end of parallel section */
```

Clause: *reduction*

- **Reductions are so common that OpenMP provides a reduction clause for the *parallel*, *for*, and *sections***

  #pragma omp … reduction (op : list)

  - **A private copy of each list variable is created and initialized depending on the *op***
    - **The identity value *op* (e.g., 0 for addition)**
  - **These copies are updated locally by threads**
  - **At end of construct, local copies are combined through *op* into a single value and combine the value in the original shared variable**

Intel, "Introduction to Parallel Programming," 2009

C/C++ Reduction Operation

- **Reduction with an associative binary operator $\oplus$**

$$a_1 \oplus a_2 \oplus a_3 \oplus \ldots \oplus a_n$$

- **A range of associative and commutative operators can be used with reduction**
- **Initial values are the ones that make sense**

Operator	Initial Value
+	0
*	1
-	0
^	0

Operator	Initial Value
&	~0
|	0
&&	1
||	0

Intel, "Introduction to Parallel Programming," 2009

Reduction: an Artificial Example

```
int sum = 3;
int prod = 5;
#pragma omp parallel for \
  reduction(+:sum)  \
  reduction(*:prod) \
  num_threads(2)
for (int i=0; i < 3; ++i) {
  int tid =
    omp_get_thread_num();
  sum |= i;
  prod += i;
  printf("thread(%d) "
         "sum=%d prod=%d\n",
         tid, sum, prod);
}
printf("results: "
       "sum=%d prod=%d\n",
       tid, sum, prod);
```

- **Assume**
  - **thread 0 executes the 1st and 2nd iterations, and**
  - **thread 1 executes the 3rd iteration**
- **Possible outputs**

```
thread(0) sum=0 prod=1
thread(1) sum=2 prod=3
thread(0) sum=1 prod=2
results: sum=6 prod=30
```

Reduction: an Artificial Example

```
int sum = 3;
int prod = 5;
#pragma omp parallel for \
  reduction(+:sum)  \
  reduction(*:prod) \
  num_threads(2)
for (int i=0; i < 3; ++i) {
  int tid =
    omp_get_thread_num();
  sum |= i;
  prod += i;
  printf("thread(%d) "
         "sum=%d prod=%d\n",
         tid, sum, prod);
}
printf("results: "
       "sum=%d prod=%d\n",
       tid, sum, prod);
```

- **initial** $sum_{private} = 0$
  - **for the reduction of +**
- **initial** $prod_{private} = 1$
  - **for the reduction of ***
- **At the end of "parallel for" with reduction**
  - $sum_{shared} \mathrel{+}= \Sigma_{thread} sum_{private}$
  - $prod_{shared} \mathrel{*}= \Pi_{thread} prod_{private}$

Strengths and Weaknesses of OpenMP

- **Strengths**
  - **Incremental parallelization & sequential equivalence**
  - **Well-suited for domain decompositions**
  - **Available on *nix and Windows**
- **Weaknesses**
  - **Not well-tailored for functional decompositions**
  - **Compilers do not have to check for such errors as deadlocks and race conditions**