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OpenMP Worksharings

Parallel Programming Workshop

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Worksharing introduction

Divide the execution of a code region among the threads of a team

- threads cooperate to do some work (i.e. to share some work)
- better way to split work than using thread-ids
- lower overhead than using tasks → less flexible

In OpenMP, there are four worksharing constructs:

- single construct
- sections construct
- loop construct
- workshare construct (only Fortran)

Restriction: worksharings cannot be nested

The single construct

Serializing (1-thread) a portion of the parallel region

- always attached to a structured block

```
#pragma omp single [clause[[,] clause]...]
{structured-block}
```

Where clause

- private(list) → explained
- firstprivate(list) → explained
- nowait
- copyprivate(list)

Only one thread of the team executes the structured block

Very useful in I/O operations

Single construct example

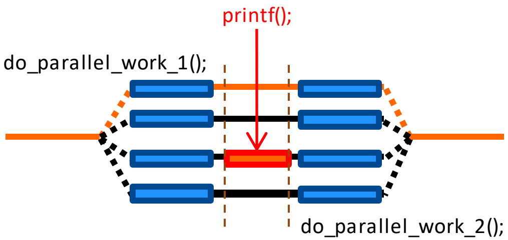
```
#include <stdio.h>

int main ( void )
{
  #pragma omp parallel
  {
    do_parallel_work_1();
    #pragma omp single
    {
      printf ("Hello world!\n" );
    }
    do_parallel_work_2();
  }
}
```

This program writes just one "Hello world!"

Implicit barrier (single)

A implicit barrier at the end of the construct

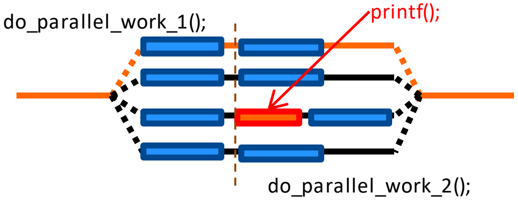
```
#pragma omp parallel
{
  do_parallel_work_1();
  #pragma omp single
  {
    printf("Hello world!\n");
  }
  do_parallel_work_2();
}
```



The nowait clause eliminates the barrier at the end of the construct

```
#pragma omp single nowait
{structured-block}
```

```
...
#pragma omp single nowait
printf("Hello world!\n");
...
```



Copying variables from/to the construct (broadcasting)

The copyprivate clause

```
#pragma omp single copyprivate(list)
{structured-block}
```

Copyprivate description

– support the broadcast of data values to other threads in the team
– apply only to private, firstprivate or threadprivate variables
– occurs after the execution of the structured block…
– … but before of the threads have left the barrier (at the end of the construct)

Copyprivate example (input data)

```
#include <stdio.h>

void main (void)
{
  float x, y;
  #pragma omp parallel private(x,y)
  {
    . . .
    #pragma omp single copyprivate(x,y)
    {
      scanf("%f %f", &x, &y);
    }
    . . .
  }
}
```

At this point variables ‘x’ and ‘y’ have been broadcasted

Single construct vs master construct

In both cases the structured block is executed by just one thread

```
#pragma omp single
{structured-block}
```

```
#pragma omp master
{structured-block}
```

The **single** construct has more overhead (additional synchronization)

- which thread has captured the token
- and the implicit barrier at the end

… but also is more flexible: any thread may execute the block

The **master** construct has less overhead

- it is just a test (if *thread-id* == 0)
- it has no implicit barrier at the end

… but also is more restrictive: only master thread may execute the block

Rule of thumb: if all threads reach the structured block at the same time use master, otherwise use single

The sections construct

Set of structured blocks distributed among threads

```
#pragma omp sections [clause[[,] clause]...]
{
   [#pragma omp section]
      {structured-block}
   [#pragma omp section
      {structured-block}]
   ...
}
```

Where clause:

- private(list) → already explained in previous constructs
- firstprivate(list) → already explained in previous constructs
- lastprivate(list)
- reduction(operator: variable-list) → already explained in previous constructs
- nowait → already explained in previous constructs

The sections construct: description (1)

Building the *syntaxis* of the sections construct

- each (selected) structured block is preceded by a section directive
- only in the first structured block the section directive is optional
- any section directive must be lexically enclosed in a sections construct

Section construct example

```
#include "synthetic.h“

void main (void)
{
  #pragma omp parallel
  #pragma omp sections
  {
    #pragma omp section
    synthetic_phase1();
    #pragma omp section
    synthetic_phase2();
    #pragma omp section
    synthetic_phase3();
  }
}
```

Only in the first structured block the section directive is optional

```
#include "synthetic.h“
void synthetic_phase2()
{
  #pragma omp section
  synthetic_phase2_1();
}
```

The sections construct: description (2)

Executing the sections construct

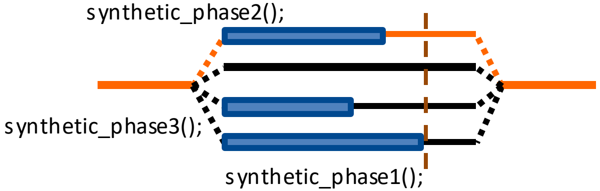
- assignment blocks/threads is implementation defined
- if no ‘nowait’ clause is present there is an implicit barrier at the end

It can be combined with the parallel construct

```
#pragma omp parallel sections [clause[[,] clause]...]
{structured-blocks: sections}
```

Using the “parallel sections” combined construct

```
void main (void)
{
  #pragma omp parallel sections
  {
    synthetic_phase1();
    #pragma omp section
    synthetic_phase2();
    #pragma omp section
    synthetic_phase3();
  }
}
```



Privatizing variables inside the construct (lastprivate)

The variable inside the construct is a new variable

- the new variables have the same type than original variable
- in any worksharing construct it means all threads have a different variable
- they can be accessed without any kind of synchronization

Already discussed privatization clauses

- private variables have undefined value when starting the block
- firstprivate variables are initialized to the value of the original one

The lastprivate clause

```
#pragma omp sections lastprivate(list)
{structured-blocks: sections}
```

- the lastprivate variables (by default) have undefined value when starting the block
- the value of the variable in the lexically last section of the set of sections is copied back to the original variable
- a variable can be both firstprivate and lastprivate

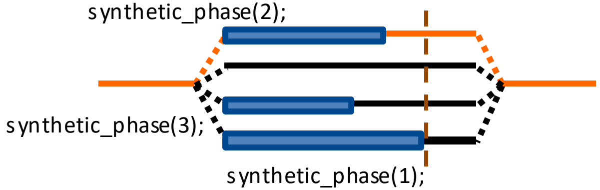
A lastprivate example (with sections construct)

Recovering the sequential consistency with the lastprivate clause

```c
#include <stdio.h>
void main (void) {
  int v = 0;
  #pragma omp parallel sections lastprivate(v)
  {
    #pragma omp section
    {  v = 1;
       synthetic_phase( v );
    }
    #pragma omp section
    {  v = 2;
       synthetic_phase( v );
    }
    #pragma omp section
    {  v = 3;
       synthetic_phase( v );
    }
  }
  printf("v = %d\n", v);
}
```

The lexically last section determines the value of the original variable

```c
#include "synthetic.h"

void synthetic_phase( int s ) {
  switch case(s)
  {
    case 1:
      matrix_multiply();
      break;
    . . .
    default:
      exit(NOT_IMPLEMENTED);
  }
}
```



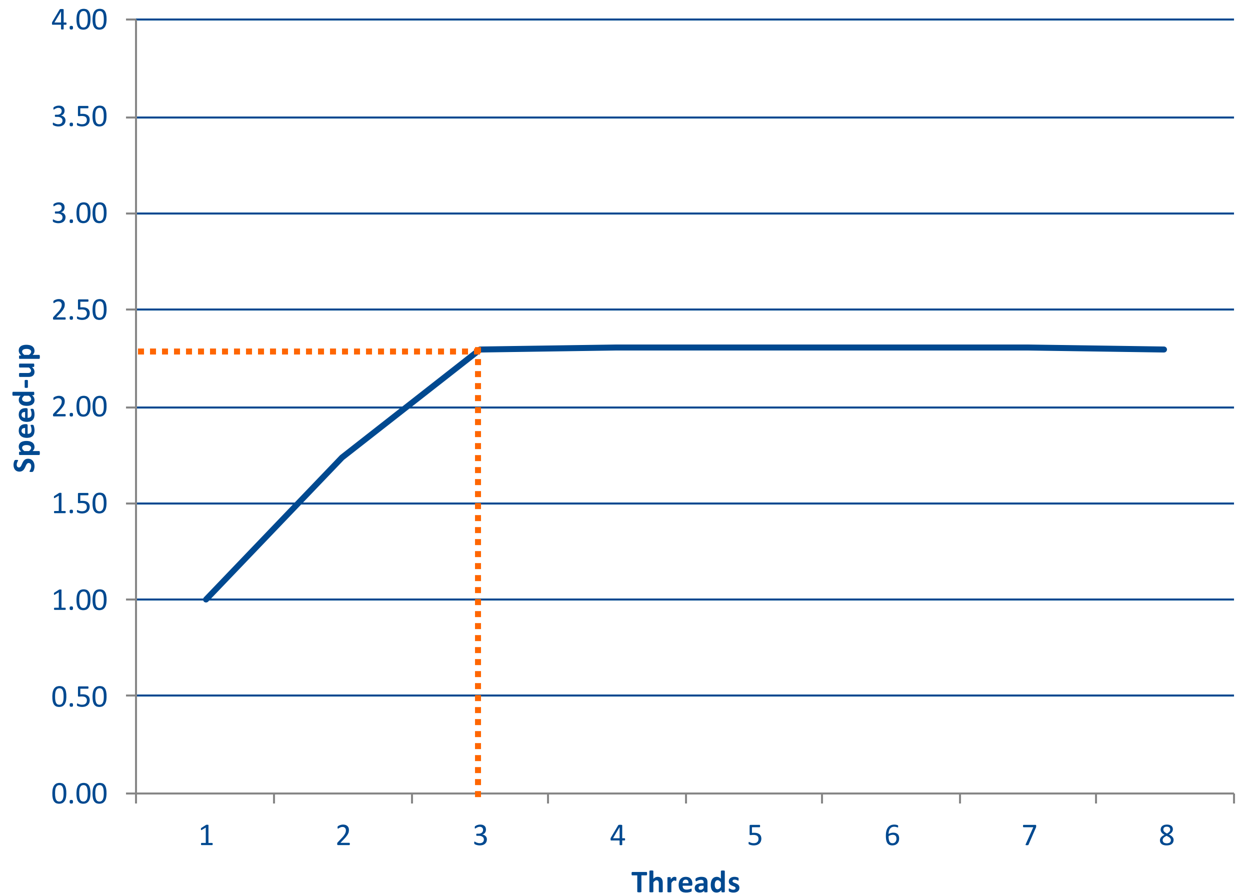
Some performance results (synthetic)

Time Results

Threads	Total Time	Speed-up
1	4,454202	1,00
2	2,562986	1,74
3	1,940174	2,30
4	1,927576	2,31
5	1,934126	2,30
6	1,929955	2,31
7	1,927792	2,31
8	1,941034	2,29
S	4,452954	1,00

$$Speedup = \frac{T_{seq}}{T_p}$$

Synthetic (sections)



The optimal amount of parallelism

Parallel decomposition (choosing the entity's granularity)

– Where entity may be a (section) structured block, or a (loop) chunk, or a task

– Parallelization [usually] may occur at different application levels
  - » **Higher levels** → coarse grain granularity
    - *Small synchronization overhead*
    - *Load imbalance (including lack of parallelism)*
  - » **Deeper levels** → fine grain granularity
    - *Greater potential for parallelism (and hence speed-up)*
    - *More synchronization overhead*

– The optimal decision is a trade off (but sometimes is difficult to find)

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Loop distribution

The loop construct

Distributing a loop among threads

- always attached to a for loop (do in Fortran)

```
#pragma omp for [clause[[,] clause]...]
{structured-block: loop}
```

Where clause:

- private(list) → already explained in previous constructs
- firstprivate(list) → already explained in previous constructs
- lastprivate(list) → already explained, but…
- reduction(operator: list) → already explained, but…
- schedule(schedule-kind)
- nowait → already explained in previous constructs
- collapse(n)
- ordered

The loop construct: description (1)

The iterations of the associated loop(s) are divided among the threads of the team

Parallel loop requirements

- loop iterations must be independent (user's responsibility)
- loops must follow a form that allows to compute the number of iterations

```
#pragma omp for [clause[[,] clause]...]
for ( init_expr; test_expr; inc_expr )
```

- valid data types for loop variables are: integers, pointers and random access iterators (in C++)

The loop construct: description (2)

It can be combined with the parallel construct

```
#pragma omp parallel for [clause[[,] clause]...]
{structured-block: loop}
```

Matrix initialization (using the loop construct)

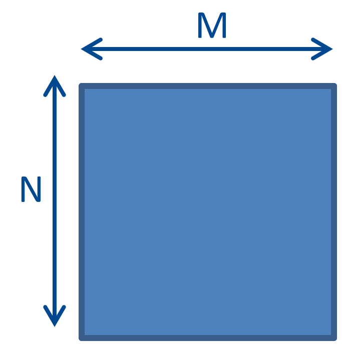
```
void foo ( int *m, int N, int M)
{
  int i, j ;
#pragma omp parallel for private( j )
  for ( i = 0; i < N; i ++ )
    for ( j = 0; j < M; j ++ )
      m[ i * N + j ] = 0;
}
```

New created threads cooperate to execute all the iterations of the loop

The i variable is automatically privatized

The j variable must be manually privatized

... but other distributions are also possible



Loop construct and the lastprivate clause

A lastprivate example

```
#pragma omp for lastprivate(list)
{structured-block: loop}
```

- lastprivate variables (by default) have undefined value when starting the block
- the value of the variable in the last logical iteration of the loop is copied back to the original variable
- a variable can be both firstprivate and lastprivate

The lastprivate clause

```
void main(void)
{
  int i;
  #pragma omp parallel
  {
    #pragma omp for lastprivate(i)
    for ( i = 0; i < n-1; i++ )
    {
      a[i] = b[i] + b[i+1];
    }
  }

  a[ i ] = b[ i ]; /* i == n-1 here */
}
```

The logical last iteration determines the value of the original variable

Loop construct and the reduction clause

All threads accumulate some values into a single variable

```
#pragma omp for reduction(operator:list)
{structured-block}
```

Reduction clause example (loop construct)

```
int vector_sum ( int n , int v [ n ] )
{
  int i , sum = 0;
  #pragma omp parallel for reduction ( + : sum)
  {
    for ( i = 0; i < n ; i ++ )
      sum += v [ i ] ;
  }
  return sum;
}
```

Private copies initialized to the identity

Shared variable updated with all the partial results

- the compiler creates a private copy that is properly initialized (identity)
- the compiler ensures that the shared variable is properly (and safely) updated with all partial results
- valid operators are: `+`, `-`, `*`, `|`, `||`, `&`, `&&`, `^`, `min`, `max`
- but we can also specify user-defined reductions

Using critical is not good enough (besides being error prone)

Loop data environment: what is the default?

Pre-determined data-sharing attributes

- *threadprivate variables are threadprivate*
- *dynamic storage duration objects are shared (malloc, new,…)*
- *static data members are shared*
- *variables declared inside the construct (static → shared / automatic → private)*
- the loop iteration variable(s) in the associated for-loop(s) of a for, parallel for, distribute or taskloop constructs is (are) private
- *the loop iteration variable in the associated (and unique) for-loop of a simd construct is linear*
- *the loop iteration variables in the associated (multiple) for-loops of a simd construct are lastprivate*

Explicit data-sharing clauses (shared, private, firstprivate,…)

- *If default clause present, what the clause says (none is very useful!!!)*

Implicit data-sharing rules, depends on the construct

- For the loop region the default data sharing attribute is shared

The loop schedule clause

The schedule clause determines which *iters* are executed by each thread in the team

```
#pragma omp for schedule(kind[,chunk-size])
{structured-block: loop}
```

- If no schedule clause is present then it is *implementation defined*

There are several possible options as schedule kind

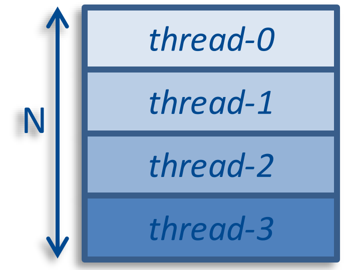
- static[, chunk-size]
- dynamic[, chunk-size]
- guided[, chunk-size]
- auto
- runtime

The loop schedule clause: static

The **static** schedule (with no chunk-size parameter)

- the iteration space is broken in chunks of approximately the same size
- then these chunks are assigned to the threads in a Round-Robin fashion

```
...
#pragma omp parallel for private( j ) schedule(static)
  for ( i = 0; i < N; i ++ )
    for ( j = 0; j < M; j ++ )
      m[ i * N + j ] = 0;
...
```



The **static** schedule (with chunk-size parameter) → interleaved

- the iteration space is broken in chunks of size N
- these chunks are assigned to the threads in a Round-Robin fashion

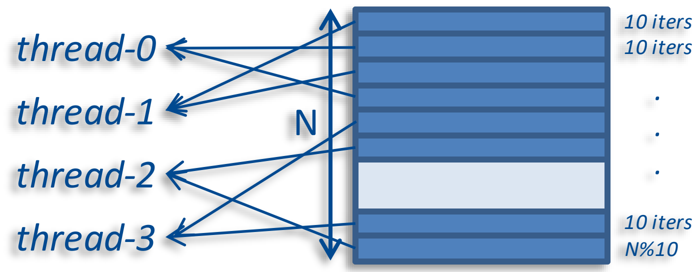
```
...
#pragma omp parallel for private( j ) schedule(static,10)
  for ( i = 0; i < N; i ++ )
    for ( j = 0; j < M; j ++ )
      m[ i * N + j ] = 0;
...
```

The loop schedule clause: dynamic & guided

The **dynamic** schedule

- if no chunk-size is specified, default is 1
- threads dynamically grab iterations until all iterations have been executed

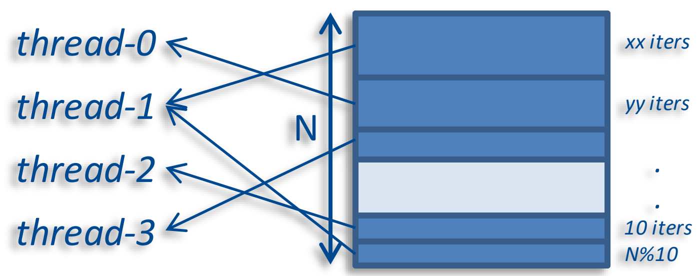
```
. . .
#pragma omp parallel for private( j ) schedule(dynamic, 10)
  for ( i = 0; i < N; i ++ )
    for ( j = 0; j < M; j ++ )
      m[ i * N + j ] = 0;
. . .
```



The **guided** schedule (variant of dynamic)

- if no chunk-size is specified, default is 1
- chunks decreases in size as threads grab iterations (at least chunk-size)

```
. . .
#pragma omp parallel for private( j ) schedule(guided, 10)
  for ( i = 0; i < N; i ++ )
    for ( j = 0; j < M; j ++ )
      m[ i * N + j ] = 0;
. . .
```



The loop schedule clause: static vs dynamic (& guided)

Static schedulers	Dynamic (and guided) schedulers
Low overhead	Higher overhead
Good Locality (usually)	Not very good locality (usually)
Can have load imbalance problems	Can solve imbalance problems

Which scheduler should work better with a specific loop?

- if all threads reach the loop region at the same time
- if all the iterations have the same weight (work)
- if consecutive loops using the same data (e.g. matrix)

static

- if threads may reach the loop at different times
- if not all the iterations have the same weight (work)

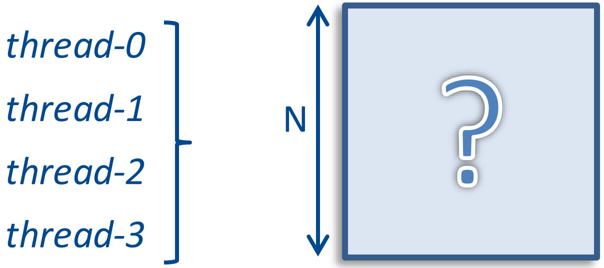
dynamic (guided)

The loop schedule clause: auto & runtime

The auto schedule (if you want to experiment)

- in this case, the implementation is allowed to do whatever it wishes
- do not expect much of it as of now

```
...
#pragma omp parallel for private( j ) schedule(auto)
  for ( i = 0; i < N; i ++ )
    for ( j = 0; j < M; j ++ )
      m[ i * N + j ] = 0;
...
```



The runtime schedule (delayed until run-time)

- using the OMP_SCHEDULE environment variable
- using the omp_set_schedule() API service call

```
...
#pragma omp parallel for private( j ) schedule(runtime)
  for ( i = 0; i < N; i ++ )
    for ( j = 0; j < M; j ++ )
      m[ i * N + j ] = 0;
...
```

```
$ export OMP_SCHEDULE=static,1024
$ ./myMatrixMultiply
Computing matrix multiplication...
```

Avoiding the implicit barrier (loop)

The nowait clause: eliminates the barrier at the end of the loop

```
#pragma omp for nowait
{structured-block}
```

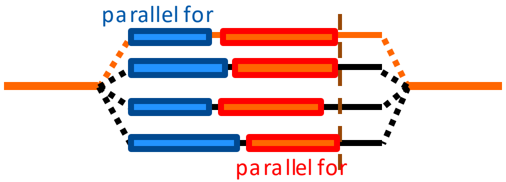
This allows to overlap the execution of non-dependent loops

```
#define N 1000
void main (void) {
  int i, a[N], b[N];

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

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

- independent iterations (in between loops) → we can overlap them
- if same iteration space → a better solution would be to (manually) fuse the loops



Avoiding the implicit barrier (loop)

The nowait clause: eliminates the barrier at the end of the loop

```
#pragma omp for nowait
{structured-block}
```

But also overlap the execution of “some” dependent loops

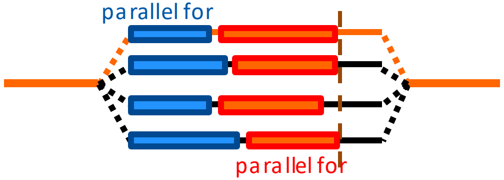
```
#define N 1000
void main (void) {
  int i, a[N], b[N];

  #pragma omp parallel
  {
    #pragma omp for schedule(static) nowait
    for ( i = 0; i < N ; i ++ )
      a [ i ] = 0;

    #pragma omp schedule(static) for
    for ( i = 0; i < N ; i ++ )
      a [ i ] = a [ i ] + foo ( i );
  }
}
```

– static scheduler, same iteration space, and dependent (on index) iterations (in between loops) → we can overlap them

– a better solution would be to (manually) fuse the loops



Avoiding the implicit barrier (loop)

The nowait clause: eliminates the barrier at the end of the loop

```
#pragma omp for nowait
{structured-block}
```

But also overlap the execution of "some" dependent loops, but not all of them

```
#define N 1000
void main (void) {
  int i, a[N], b[N];

  #pragma omp parallel
  {
    #pragma omp for schedule(dynamic) nowait
    for ( i = 0; i < N ; i ++ )
      a [ i ] = 0;

    #pragma omp for schedule(dynamic)
    for ( i = 0; i < N ; i ++ )
      a [ i ] = a [ i ] + foo ( i );;
  }
}
```

- no static scheduler: same iteration space, and dependant (on index) iterations (in between loops) → NO
  - a solution would be to (manually) fuse the loops
- not the same iteration space: static scheduler and dependent (on index) iterations (in between loops) → NO
- dependence (arbitrary in any index): same iteration space and static scheduler → NO

The collapse clause

Allows to distribute work from a set of *n*-nested loops

- loops must be perfectly nested (no instruction in between)
- the nest must traverse a rectangular iteration space
- combines both iteration spaces to create a single one

Using the collapse clause over two loops

```
#define N ??
#define M ???

void main (void) {
  int i, j;
  #pragma omp parallel
  {
    #pragma omp for collapse(2)
    for ( i = 0; i < N; i ++ )
      for ( j = 0; j < M; j ++ )
        foo ( i , j );
  }
}
```

- useful when first loop (or both) have only a few iterations (e.g., N = 64)
- increase the amount of created parallelism

```
#pragma omp for
for ( idx = 0; idx < (N * M); idx ++ ) {
   foo ( fi(idx), fj(idx) );
}
```

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Additional synchronization

Synchronizing the execution

Threads need to impose some ordering in the sequence of their actions

- execute in a logical order certain regions
- mutual exclusion in the execution of a given region
- wait in a location until all other threads have reach the same location
- wait until a given condition is accomplished

OpenMP provides different synchronization mechanisms

- master construct→ already explained in previous sessions
- critical construct → already explained in previous sessions
- barrier directive
- atomic construct
- taskwait directive → will be explained in following sessions (tasking)
- taskgroup construct → will be explained in following session (tasking)
- depend clause → will be explained in following sessions (tasking)

The barrier directive

Threads cannot proceed after a barrier point until

- all threads reach the barrier
- and all previously generated work is completed

```
#pragma omp barrier
```

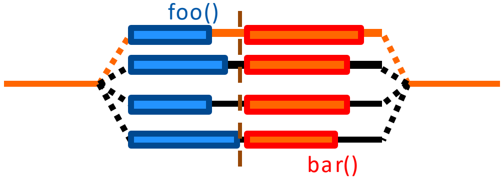
- some constructs have an implicit barrier at the end (e.g., the parallel construct)

Synchronizing threads between two phases in a parallel region

```
#pragma omp parallel
{
  foo ();
  #pragma omp barrier
  bar ();
}
```

Forces all foo()'s too happen before all bar()'s

Implicit barrier



Mutual exclusion for simple read & update operations

The atomic construct

- special mechanism of mutual exclusion to "read & update" operations
- only supports simple read & update expressions
  - e.g., x += 1 → whole expression is protected
  - x = x - foo() → only protects the read & update part, foo() is not protected

Usually it is much more efficient than a critical construct…

… but it is not compatible/interop with it →

```c
int x =1;
#pragma omp parallel num_threads( 2 )
{
  #pragma omp atomic
  x++;
}
printf("%d\n", x );
```

Only one thread at a time updates x here

Prints "3"

```c
int x =1;
#pragma omp parallel num_threads( 2 )
{
  #pragma omp atomic
  x++;
  . . .
  #pragma omp critical
  x++;
}
printf("%d\n", x );
```

May execute an atomic and a critical block at the "same time"

Prints "?"

The atomic construct is just an additional mechanism to fix data races

Summary: OpenMP worksharings

OpenMP worksharings: single, section, loop and workshare

- distribute work among threads without using thread-id (neither *num*-threads)
- parallel decomposition trade off: coarse and fine granularity
- control how the work is distribute (loop) using the schedule clause
- new ways to control the data environment in these news constructs

Additional synchronization constructs

- the barrier directive →synchronize threads
- the atomic directive → other mechanism to fix data races

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Thank you!

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