

Parallelism (PAR)

Short tutorial on OpenMP

A. Durán and E. Ayguadé

Barcelona Supercomputing Center and Computer Architecture Department

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Part I

OpenMP Basics



Outline

- OpenMP overview
- OpenMP model
- Creating threads and accessing data
- Some API calls
- Thread synchronization
- Memory consistency



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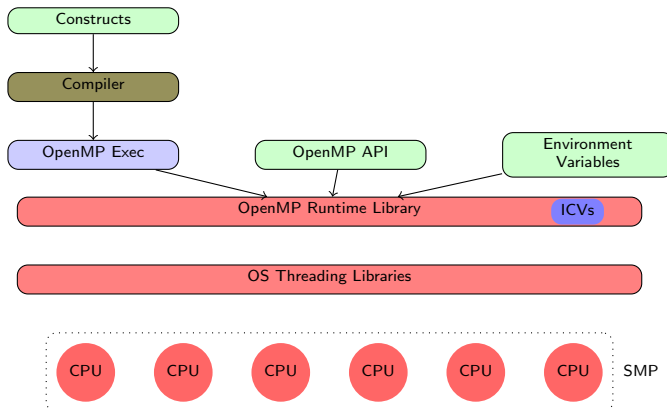
What is OpenMP?

- ▶ It's an API extension to the C, C++ and Fortran languages to write parallel programs for shared memory machines
 - ▶ Current version is 4.0 (July 2013)
 - ▶ Supported by most compiler vendors
 - ▶ Intel, IBM, PGI, Sun, Cray, Fujitsu, HP, GCC,...
- ▶ Maintained by the Architecture Review Board (ARB), a consortium of industry and academia
- ▶ This mini-tutorial just covers part of the specification, for the complete reference please consult the documentation online

<http://www.openmp.org>



OpenMP components



OpenMP components

Constructs

These form the major elements of OpenMP programming

- ▶ Create threads
- ▶ Share the work amongst threads
- ▶ Synchronize threads and memory

Library routines

To control and query the parallel execution environment (internal control variables - ICVs)

Environment variables

The execution environment can also be set before the program execution is started



OpenMP directives syntax

In C/C++

Through a compiler directive:

```
#pragma omp construct [clauses]
```

- ▶ OpenMP syntax is ignored if the compiler does not recognize OpenMP

Structured block

Most directives apply to:

- ▶ A block of one or more statements
- ▶ One entry point, one exit point
 - ▶ No branching in or out allowed



Headers/Macros

C/C++ only

- ▶ `omp.h` contains the API prototypes and data types definitions
- ▶ The `_OPENMP` is defined by OpenMP enabled compiler
 - ▶ Allows conditional compilation of OpenMP



Outline

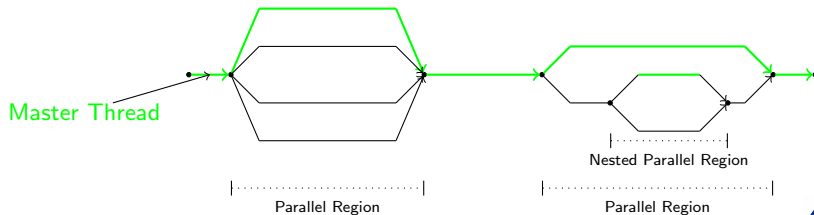
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Execution model

Fork-join model

- ▶ OpenMP uses a **fork-join** model
 - ▶ The **master** thread spawns a **team** of threads that joins at the end of the parallel region
 - ▶ Threads in the same team can **collaborate** to do work



Memory model

- ▶ OpenMP defines a relaxed memory model
 - ▶ Threads can see different values for the same variable
 - ▶ Memory consistency is only guaranteed at specific points
 - ▶ Luckily, the default points are usually enough
 - ▶ If not ... there is a mechanism to guarantee it! (described at the end of Part I)
- ▶ Variables can be shared or private to each thread



Outline

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The parallel construct

Directive

```
#pragma omp parallel [clauses]  
    structured block
```

where some of the **clauses** are:

- ▶ `num_threads(expression)`
- ▶ `if(expression)`
- ▶ `shared(var-list)`
- ▶ `private(var-list)`
- ▶ `firstprivate(var-list)`
- ▶ `reduction(operator:var-list)`

Coming shortly!

We'll see it later



The parallel construct

Specifying the number of threads

- ▶ The `nthreads-var` ICV is used to determine the number of threads to be used for encountered parallel regions
 - ▶ It is a list of positive integer values, its first element specifying the number of processors for the next nesting level
 - ▶ When a `parallel` construct is encountered, and the generating task's `nthreads-var` list contains multiple elements, the generated task(s) inherit the value of `nthreads-var` as the list obtained by deletion of the first element
 - ▶ If the generating task's `nthreads-var` list contains a single element, the generated task(s) inherit that list as the value of `nthreads-var`



The parallel construct

Specifying the number of threads

- ▶ The `nthreads-var` list can be defined from the execution command line by setting the `OMP_NUM_THREADS` environment variable
 - ▶ Example: `setenv OMP_NUM_THREADS 4,3,2`
- ▶ After that, the `threads-var` list can be modified through:
 - ▶ the `omp_set_num_threads` API, which sets the value of the first element of the current list
 - ▶ the `num_threads` clause, which causes the implementation to ignore the ICV and use the value of the clause for that region.



The if clause

Avoiding parallel regions

- ▶ Sometimes we only want to run in parallel under certain conditions
 - ▶ E.g., enough input data, not running already in parallel, ...
- ▶ The `if` clause allows to specify an *expression*. When evaluates to false the `parallel` construct will only use 1 thread
 - ▶ Note that still creates a new team and data environment



The parallel construct

```
void main () {  
    #pragma omp parallel  
    ...  
    omp_set_num_threads(2);  
    #pragma omp parallel  
    ...  
    #pragma omp parallel num_threads(random()%4+1) if(0)  
    ...  
}
```

How many threads are used in each parallel region above?



Data-sharing attributes

Shared

When a variable is marked as `shared`, the variable inside the construct is the same as the one outside the construct

- ▶ In a parallel construct this means all threads see the same variable
 - ▶ but not necessarily the same value
- ▶ Usually need some kind of synchronization to update them correctly
 - ▶ OpenMP has consistency points at synchronizations
- ▶ By default, variables are implicitly `shared`



Data-sharing attributes

Private

When a variable is marked as `private`, the variable inside the construct is a `new` variable of the same type with an `undefined` value

- ▶ In a parallel construct this means all threads have a different variable
- ▶ Can be accessed without any kind of synchronization



Data-sharing attributes

Firstprivate

When a variable is marked as `firstprivate`, the variable inside the construct is a `new` variable of the same type but it is initialized to the original variable value

- ▶ In a parallel construct this means all threads have a different variable with the same initial value
- ▶ Can be accessed without any kind of synchronization



Data-sharing attributes

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

What does appear on the screen if **XXXXXX** is **shared(x)**, **private(x)** or **firstprivate(x)**?



Example: computation of PI

```
static long num_steps = 100000;
double step;
void main ()
{
    int i;
    double x, pi, sum = 0.0;

    step = 1.0/(double) num_steps;

    for (i=1;i<= num_steps; i++){
        x = (i-0.5)*step;
        sum = sum + 4.0/(1.0+x*x);
    }
    pi = step * sum;
}
```



Example: computation of π (not equivalent to sequential!)

```
static long num_steps = 100000;
double step;
#include <omp.h>
#define NUM_THREADS 2
void main ()
{
    int i, id;
    double x, pi, sum=0.0;

    step = 1.0/((double) num_steps);
    omp_set_num_threads(NUM_THREADS);
    #pragma omp parallel private(x, i)
    for (i=1;i<= num_steps; i++){
        x = (i-0.5)*step;
        sum = sum + 4.0/(1.0+x*x);
    }

    pi = sum * step;
}
```



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- **Some API calls**
- Thread synchronization
- Memory consistency



Some useful routines

<code>int omp_get_num_threads()</code>	Returns the number of threads in the current team. 1 if outside a parallel region
<code>int omp_get_thread_num()</code>	Returns the id of the thread in the current team. id between 0 and <code>omp_get_num_threads()-1</code>
<code>void omp_set_num_threads()</code>	Sets the number of threads to be used in parallel regions at the next nesting level
<code>int omp_get_max_threads()</code>	Returns the number of threads that could be used in parallel regions at the next nesting level
<code>double omp_get_wtime()</code>	Returns the number of seconds since an arbitrary point in the past



Example: computation of PI (data race!)

```
static long num_steps = 100000;
double step;
#include <omp.h>
#define NUM_THREADS 2
void main ()
{
    int i, id;
    double x, pi, sum=0.0;

    step = 1.0/((double) num_steps);
    omp_set_num_threads(NUM_THREADS);
    #pragma omp parallel private(x, i, id)
    {
        id = omp_get_thread_num();
        for (i=id+1; i<=num_steps; i=i+NUM_THREADS) {
            x = (i-0.5)*step;
            sum = sum + 4.0/(1.0+x*x);
        }
    }
    pi = sum * step;
}
```



Example: computation of PI (measuring execution time)

```
static long num_steps = 100000;
double step;
#include <omp.h>
#define NUM_THREADS 2
void main ()
{
    int i, id;
    double x, pi, sum=0.0;
    double TimeStart, TimeEnd;

    TimeStart = omp_get_wtime();
    step = 1.0/((double) num_steps);
    omp_set_num_threads(NUM_THREADS);
    #pragma omp parallel private(x, i, id)
    {
        ...
    }
    pi = sum * step;
    TimeEnd = omp_get_wtime();
    printf("Wallclocktime=%%.20f\n", TimeEnd-TimeStart);
}
```



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Why synchronization?

OpenMP is a shared memory model

- ▶ Threads communicate by sharing variables
- ▶ Unintended sharing of data causes race conditions (i.e. the execution outcome may change as the threads are scheduled differently)
- ▶ Threads need to synchronize to impose some ordering in their sequence of actions

Some OpenMP synchronization mechanisms:

- ▶ `barrier`
- ▶ `critical`
- ▶ `atomic`
- ▶ Use of locks through API



Thread Barrier

The barrier construct

```
#pragma omp barrier
```

- ▶ Threads cannot proceed past a barrier point until all threads reach the barrier **AND** all previously generated work is completed
- ▶ Some constructs have an implicit **barrier** at the end
 - ▶ E.g., the **parallel** construct



Barrier

Example

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

Forces all **foo** occurrences too
happen before all **bar** occurrences

Implicit barrier at the end of the **parallel** region



Exclusive access: critical construct

```
#pragma omp critical [(name)]  
    structured block
```

- ▶ Provides a region of mutual exclusion where only one thread can be working at any given time
- ▶ By default all critical regions are the same
- ▶ Multiple mutual exclusion regions by providing them with a name
 - ▶ Only those with the same name synchronize



Example: computation of PI

```

...
void main ()
{
    int i, id;
    double x, pi, sum=0.0;

    step = 1.0/((double) num_steps;
    omp_set_num_threads(NUM_THREADS);
    #pragma omp parallel private(x, i, id)
    {
        id = omp_get_thread_num();
        for (i=id+1; i<=num_steps; i=i+NUM_THREADS) {
            x = (i-0.5)*step;
            #pragma omp critical
            sum = sum + 4.0/(1.0+x*x);
        }
    }
    pi = sum * step;
}

```



Critical construct

```
int x=1,y=0;
#pragma omp parallel num_threads(4)
{
  #pragma omp critical (x)
    x++;
  #pragma omp critical (y)
    y++;
}
```

Different names: One thread can update x while another updates y



Exclusive access: atomic construct

```
#pragma omp atomic [update | read | write]  
expression
```

- ▶ Ensures that a specific storage location is accessed atomically, avoiding the possibility of multiple, simultaneous reading and writing threads
 - ▶ Atomic updates: `x += 1`, `x = x - foo()`, `x[index[i]]++`
 - ▶ Atomic reads: `value = *p`
 - ▶ Atomic writes: `*p = value`
- ▶ Only protects the read/operation/write
- ▶ Usually more efficient than a `critical` construct
- ▶ Other clauses and forms for `atomic` are allowed in the specification



First example: computation of PI

```
...
void main ()
{
    int i, id;
    double x, pi, sum=0.0;

    step = 1.0/((double) num_steps;
    omp_set_num_threads(NUM_THREADS);
    #pragma omp parallel private(x, i, id)
    {
        id = omp_get_thread_num();
        for (i=id+1; i<=num_steps; i=i+NUM_THREADS) {
            x = (i-0.5)*step;
            #pragma omp atomic
            sum = sum + 4.0/(1.0+x*x);
        }
    }
    pi = sum * step;
}
```



The reduction clause

Reduction is a very common pattern where all threads accumulate values into a single variable

`reduction(operator : list)`

- ▶ Valid operators are: `+, -, *, |, ||, &, &&, ^`
- ▶ The compiler creates a `private` copy of each variable in list that is properly initialized to the identity value
- ▶ At the end of the region, the compiler ensures that the `shared` variable is properly (and safely) updated with the partial values of each thread, using the specified operator



First example: computation of PI

```
...
void main ()
{
    int i, id;
    double x, pi, sum;

    step = 1.0/((double) num_steps;
    omp_set_num_threads(NUM_THREADS);
    #pragma omp parallel private(x, i, id) reduction(+:sum)
    {
        id = omp_get_thread_num();
        for (i=id+1; i<=num_steps; i=i+NUM_THREADS) {
            x = (i-0.5)*step;
            sum = sum + 4.0/(1.0+x*x);
        }
    }
    pi = sum * step;
}
```



Locks

OpenMP provides **lock** primitives for low-level synchronization

<code>omp_init_lock</code>	Initialize the lock
<code>omp_set_lock</code>	Acquires the lock
<code>omp_unset_lock</code>	Releases the lock
<code>omp_test_lock</code>	Tries to acquire the lock (won't block)
<code>omp_destroy_lock</code>	Frees lock resources



Locks

Example

```
#include <omp.h>
void foo ()
{
    omp_lock_t lock;

    omp_init_lock(&lock);
    #pragma omp parallel
    {
        omp_set_lock(&lock);
        // mutual exclusion region
        omp_unset_lock(&lock);
    }
    omp_destroy_lock(&lock);
}
```

Lock must be initialized before being used

Only one thread at a time here



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The flush construct

Relaxed consistency memory model

- ▶ A thread's temporary view of memory is not required to be consistent with memory at all times
- ▶ A value written to a variable can remain in the thread's temporary view until it is forced to memory at a later time
- ▶ Likewise, a read from a variable may retrieve the value from the thread's temporary view, unless it is forced to read from memory



The flush construct

```
#pragma omp flush ( list )
```

- ▶ It enforces consistency between the temporary view and memory for those variables in list
- ▶ Synchronization (implicit or explicit) constructs have an associated flush operation



Part II

Loop Parallelism in OpenMP



Outline

- The worksharing concept
- Loop worksharing
- The single construct



Outline

- The worksharing concept
- Loop worksharing
- The single construct



The worksharing concept

Worksharing constructs divide the execution of a code region among the members of a team

- ▶ Threads **cooperate** to do some work
- ▶ Better way to split work than using thread-ids
- ▶ Lower overhead than using **tasks** (next section)
 - ▶ But, less flexible

In OpenMP, there are four worksharing constructs:

- ▶ loop worksharing
- ▶ **single** ← We'll see it later
- ▶ **sections** ←
- ▶ **workshare** ← Not used much ... we'll skip them



Outline

- The worksharing concept
- Loop worksharing
- The single construct



Loop parallelism

The for construct

```
#pragma omp for [clauses]  
    for( init-expr ; test-expr ; inc-expr )
```

where some possible clauses are:

- ▶ `private`
- ▶ `firstprivate`
- ▶ `reduction`
- ▶ `schedule(schedule-kind)`
- ▶ `nowait`
- ▶ `collapse(n)`



The for construct

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

- ▶ Loop iterations must be independent
- ▶ Loops must follow a form that allows to compute the number of iterations
- ▶ Valid data types for inductions variables are: integer types, pointers and random access iterators (in C++)
 - ▶ The induction variable(s) are automatically privatized
- ▶ The default data-sharing attribute is **shared**

It can be merged with the **parallel** construct:

```
#pragma omp parallel for
```



First example: computation of PI

```
#include <omp.h>
static long num_steps = 100000;
double step;
#define NUM_THREADS 2

void main ()
{
    int i, id;
    double x, pi, sum;

    step = 1.0/(double) num_steps;
    omp_set_num_threads(NUM_THREADS);
    #pragma omp parallel for private(x) reduction(+:sum)
    for (i=1; i<=num_steps; i++) {
        x = (i-0.5)*step;
        sum = sum + 4.0/(1.0+x*x);
    }
    pi = sum * step;
}
```



The schedule clause

The `schedule` clause determines which iterations are executed by each thread.

- ▶ If no `schedule` clause is present then is implementation defined

There are several possible options as schedule:

- ▶ `static[,chunk]`
- ▶ `dynamic[,chunk]`
- ▶ `guided[,chunk]`



The schedule clause

`static`

The iteration space is broken in chunks of approximately size $N/\text{num_threads}$. Then these chunks are assigned to the threads in a Round-Robin fashion.

`static,N` (also called interleaved)

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

Characteristics of static schedules

- ▶ Low overhead
- ▶ Good locality (usually)
- ▶ Can have load imbalance problems



The schedule clause

`dynamic,N`

Threads dynamically grab chunks of N iterations until all iterations have been executed. If no chunk is specified, $N = 1$.

`guided,N`

Variant of `dynamic`. The size of the chunks decreases as the threads grab iterations, but it is at least of size N . If no chunk is specified, $N = 1$.

Characteristics of dynamic schedules

- ▶ Higher overhead
- ▶ Not very good locality (usually)
- ▶ Can solve imbalance problems



The nowait clause

When a worksharing has a **nowait** clause then the implicit **barrier** at the end of the loop is removed.

- This allows to overlap the execution of **non-dependent** loops/tasks/worksharings

```
#pragma omp for nowait  
for ( i = 0; i < n ; i++ )  
    v[i] = 0;  
#pragma omp for  
for ( i = 0; i < n ; i++ )  
    a[i] = 0;
```

First and second loop are independent so we can overlap them



The nowait clause

Useful to overlap the execution of two (or more) consecutive loops if they have the same **static** schedule and all have the same number of iterations.

```
#pragma omp for schedule(static,2) nowait
for ( i = 0; i < n ; i++ )
    v[i] = 0;
#pragma omp for schedule(static,2)
for ( i = 0; i < n ; i++ )
    a[i] = v[i]*v[i];
```



The collapse clause

Allows to distribute work from a set of n nested loops.

- ▶ Loops must be perfectly nested
- ▶ The nest must traverse a rectangular iteration space

```
#pragma omp for collapse(2)
for ( i = 0; i < N; i++ )
    for ( j = 0; j < M; j++ )
        foo ( i , j );
```

i and j loops are folded and iterations distributed among all threads.
Both i and j are privatized



Outline

- The worksharing concept
- Loop worksharing
- The single construct



Giving work to just one thread

The single construct

```
#pragma omp single [clauses]  
    structured block
```

- ▶ where clauses can be:
 - ▶ `private`
 - ▶ `firstprivate`
 - ▶ `nowait`
- ▶ **Only one** thread of the team executes the structured block
- ▶ There is an implicit **barrier** at the end



Part III

Task Parallelism in OpenMP



Outline

- OpenMP tasks
- Task synchronization



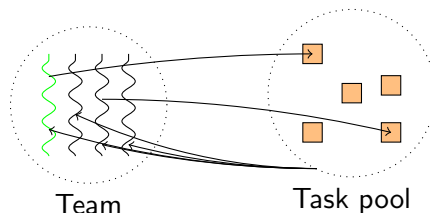
Outline

- OpenMP tasks
- Task synchronization



Task parallelism model

- ▶ Tasks are work units whose execution **may** be deferred
 - ▶ they can also be executed immediately
- ▶ Threads of the team **cooperate** to execute them



Creating tasks

Implicit and explicit tasks

- ▶ `Parallel` regions create tasks
 - ▶ One `implicit` task is created and assigned to each thread
- ▶ Each thread that encounters a `task` construct
 - ▶ Packages the code and data
 - ▶ Creates a new `explicit` task



Creating (explicit) tasks

The task construct

```
#pragma omp task [clauses]  
    structured block
```

Where some possible clauses are:

- ▶ `shared`
- ▶ `private`
- ▶ `firstprivate`
 - ▶ Values are captured at `creation time`
- ▶ `if(expression)`
- ▶ `final(expression)`
- ▶ `mergeable`



Example: list traversal

```
void traverse_list ( List l )  
{  
    Element e;  
    for ( e = l->first; e ; e = e->next )  
        #pragma omp task  
        process(e);  
}
```



Example: list traversal

Completing the picture

We need threads to execute the tasks ...

List l

```
#pragma omp parallel
traverse_list(l);
...

void traverse_list ( List l )
{
    Element e;
    for ( e = l->first; e ; e = e->next )
        #pragma omp task // e is firstprivate by default
        process(e);
}
```

... but not that many! This will generate multiple traversals



Example: list traversal

Using `single` ...

List l

```
#pragma omp parallel
#pragma single
traverse_list(l);
...

void traverse_list ( List l )
{
    Element e;
    for ( e = l->first; e ; e = e->next )
        #pragma omp task
        process(e);
}
```

One thread creates the tasks of the traversal. The rest (and this one once task generation is finished) `cooperate` to execute them



Default task data-sharing attributes

When no data clauses are specified, some rules apply:

- ▶ Global variables are shared
- ▶ Variables declared in the scope of a task are private
- ▶ The rest are `firstprivate` except when a `shared` attribute can be lexically inherited



Task default data-sharing attributes

In practice...

```
int a;  
void foo() {  
    int b,c;  
    #pragma omp parallel shared(b)  
    #pragma omp parallel private(b)  
    {  
        int d;  
        #pragma omp task  
        {  
            int e;  
  
            a = // shared  
            b = // firstprivate  
            c = // shared  
            d = // firstprivate  
            e = // private  
  
        }  
    }  
}
```



The `if` clause: immediate task execution

- ▶ If the expression of an `if` clause evaluates to `false`
 - ▶ The encountering task is suspended
 - ▶ The new task is `executed immediately`
 - ▶ with its own data environment
 - ▶ different task with respect to synchronization
 - ▶ The parent task resumes when the task finishes
 - ▶ Allows implementations to `optimize` task creation



The `final` clause: immediate task execution (nested)

- ▶ If the expression of a `final` clause evaluates to `true`
 - ▶ The generated task and all of its child tasks will be final
 - ▶ The execution of a final task is sequentially **included** in the generating task (executed immediately)
- ▶ When a `mergeable` clause is present on a task construct, and the generated task is an **included** task, the implementation may generate a merged task instead (i.e. no task and context creation for it).



Final and mergeable tasks (data race!)

```
int fib(int n) {  
    int i, j;  
  
    if (n<2)  
        return n;  
    #pragma omp task shared(i) final(n <= THOLD) mergeable  
    i=fib(n-1);  
    #pragma omp task shared(j) final(n <= THOLD) mergeable  
    j=fib(n-2);  
  
    ....  
  
    return i+j;  
}
```



Outline

- OpenMP tasks
- Task synchronization



Task synchronization

There are two types of task barriers:

- ▶ `taskwait`
 - ▶ Suspends the current task waiting on the completion of **child tasks** of the current task. The `taskwait` construct is a stand-alone directive
- ▶ `taskgroup`
 - ▶ Suspends the current task at the end of structured block waiting on completion of **child tasks** of the current task **and their descendent** tasks.



Taskwait

```
#pragma omp taskwait
```

```
#pragma omp task {}           // T1  
#pragma omp task              // T2  
{  
    #pragma omp task {}      // T3  
}  
#pragma omp task {}           // T4  
  
#pragma omp taskwait  
    ←  
}
```

Only T1, T2 and T4 are guaranteed to have finished here



Taskwait for correct Fibonacci parallelization

```
int fib(int n) {  
    int i, j;  
  
    if (n<2)  
        return n;  
    #pragma omp task shared(i) final(n <= THOLD) mergeable  
    i=fib(n-1);  
    #pragma omp task shared(j) final(n <= THOLD) mergeable  
    j=fib(n-2);  
  
    #pragma omp taskwait  
    return i+j;  
}
```



Taskgroup

```
#pragma omp taskgroup  
    structured block
```

```
#pragma omp task {}           // T1  
#pragma omp taskgroup  
{  
    #pragma omp task           // T2  
    {  
        #pragma omp task {}    // T3  
    }  
    #pragma omp task {}       // T4  
}
```

← Only T2, T3 and T4 are guaranteed to have finished here



Data sharing inside tasks

In addition one can use `critical` and `atomic` to synchronize the access to shared data inside the task

```
void process (Element e)
{
    ...
    #pragma omp atomic
    solutions_found++;
    ...
}
```



Task dependences

Definition of dependences between sibling tasks (i.e. from the same father)

```
#pragma omp task [depend (in : var_list)]  
                  [depend (out : var_list)]  
                  [depend (inout : var_list)]
```

Task dependences are derived from the dependence type (in, out or inout) and its items in `var_list`. This list may include array sections



Task dependences

- ▶ The `in` dependence-type: the generated task will be a dependent task of all previously generated sibling tasks that reference at least one of the list items in an `out` or `inout` dependence-type list
- ▶ The `out` and `inout` dependence-types: the generated task will be a dependent task of all previously generated sibling tasks that reference at least one of the list items in an `in`, `out`, or `inout` dependence-type list.



Task dependences

Example: wave-front execution

```
#pragma omp parallel private(j)
#pragma omp single
{
    for (i=1; i<n; i++) {
        for (j=1; j<n; j++) {
            #pragma omp task
                depend(in : block[i-1][j], block[i][j-1])
                depend(out: block[i][j])
            foo(i, j);
        }
    }
}
```



Parallelism (PAR)

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A. Durán and E. Ayguadé

Barcelona Supercomputing Center and Computer Architecture Department

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