

# Parallelism (PAR)

## Short tutorial on OpenMP 5.0 tasking

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# Part I

## OpenMP Basics



# Outline

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



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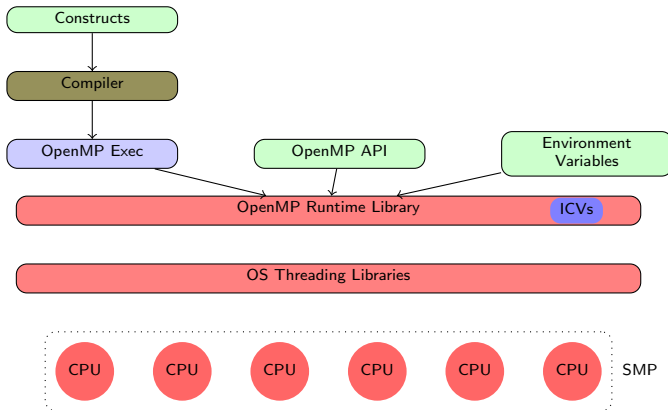
# What is OpenMP?

- ▶ It's an API extension to the C, C++ and Fortran languages to write parallel programs for shared memory machines
  - ▶ Current version is 5.0 (November 2018)
  - ▶ Supported by most compiler vendors and implementors
    - ▶ Intel, IBM, PGI, GCC, LLVM, ...
- ▶ 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 and tasks
- ▶ Share the work amongst threads and accelerators (not covered in this mini-tutorial)
- ▶ Synchronize threads and memory, and wait for termination of tasks

## 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 have the appropriate compilation flag activated

## 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

```
#ifdef _OPENMP
    printf("Parallel execution with %d threads\n",
           omp_get_num_threads());
#endif
```



# Outline

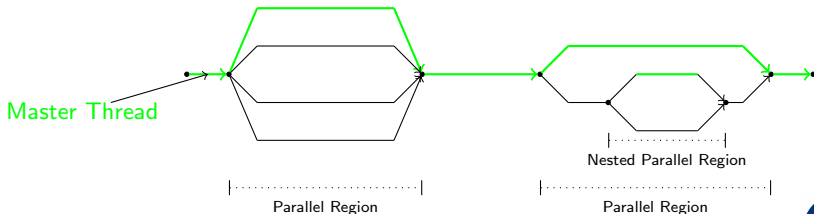
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# Execution model

## 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



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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 PI (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 useful routines

int `omp_get_num_threads()`

Returns the **number** of threads in the **current** team. 1 if outside a parallel region

int `omp_get_thread_num()`

Returns the **id** of the thread in the **current** team. **id** between 0 and `omp_get_num_threads()-1`

void `omp_set_num_threads()`

Sets the **number** of threads to be used in parallel regions at the next nesting level

int `omp_get_max_threads()`

Returns the **number** of threads that could be used in parallel regions at the next nesting level

double `omp_get_wtime()`

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("Wall clock time = %.20f\n", TimeEnd-TimeStart);
}
```



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# Only one thread in the team doing the work

## 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



## The nowait clause

When `single` has a `nowait` clause then the implicit `barrier` at the end of the `single` is removed.

- ▶ This allows to overlap the execution of `non-dependent` work inside `single` with what continues after it.

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

First and second single regions are independent so we can overlap them



## Example: computation of PI with single

```
...  
void main ()  
{  
    ...  
    #pragma omp parallel private(x, i) firstprivate(sum)  
    {  
        #pragma omp single nowait  
        {  
            for (i=1; i<=num_steps; i++) {  
                x = (i-0.5)*step;  
                sum = sum + 4.0/(1.0+x*x);  
            }  
            pi = sum * step;  
        }  
        if (sum==0.0)  
            printf("Life is good when there is nothing to do...\n");  
    }  
}
```





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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 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: `+, -, *, |, ||, &, &&, ^, min, max`
- ▶ 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);
```

Lock must be initialized before being used

```
    #pragma omp parallel
```

```
    {
```

```
        omp_set_lock(&lock);
```

```
        // mutual exclusion region
```

```
        omp_unset_lock(&lock);
```

Only one thread at a time here

```
    }
```

```
    omp_destroy_lock(&lock);
```

```
}
```



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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

# Task Parallelism in OpenMP



# Outline

- OpenMP tasks
- Task synchronization
- Taskloop construct
- Reductions in the tasking model



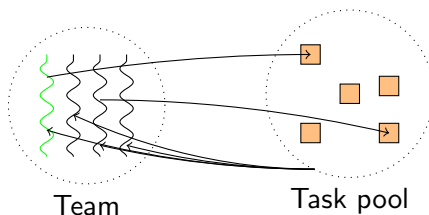
# Outline

- OpenMP tasks
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## 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

- ▶ A `parallel` region creates tasks
  - ▶ One `implicit` task is created and assigned to each thread in the team of threads
- ▶ 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 omp 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  
    {  
        #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
    - ▶ as a different task with respect to synchronization
  - ▶ The parent task resumes when the new 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
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# 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(i, 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);
        }
    }
}
```



# Outline

- OpenMP tasks
- Task synchronization
- **Taskloop construct**
- Reductions in the tasking model





# Creating (explicit) tasks from loop iterations

## The taskloop construct

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

specifies that the iterations of one or more associated loops will be executed in parallel using OpenMP tasks. Implicit **taskgroup** synchronization associated with **taskloop**

Some clauses are used to specify data sharing attributes:

- ▶ **shared(list)**
- ▶ **private(list)**
- ▶ **firstprivate(list)**



# Creating (explicit) tasks from loop iterations

Other clauses to control task generation:

- ▶ `grainsize(n)`
- ▶ `num_tasks(n)`
- ▶ `collapse(n)`
- ▶ `if(expression)`
- ▶ `final(expression)`
- ▶ `mergeable`

Or to override the implicit `taskgroup` associated with the `taskloop` construct:

- ▶ `nogroup`



## Taskloop example

Granularity: BS iterations per task

```
void vector_add(int *A, int *B, int *C, int n) {  
    #pragma omp taskloop grainsize(BS)  
    for (int i=0; i< n; i++)  
        C[i] = A[i] + B[i];  
}  
void main() {  
    #pragma omp parallel  
    #pragma omp single  
    ... vector_add(a, b, c, N); ...  
}
```

or alternatively

```
#pragma omp taskloop num_tasks(n/BS)
```



# Outline

- OpenMP tasks
- Task synchronization
- Taskloop construct
- Reductions in the tasking model



# Reduction clauses

## Directives and clauses associated

```
#pragma omp taskloop  
    [{reduction | in_reduction}(op: list )}]
```

```
#pragma omp task [in_reduction(op: list )]
```

```
#pragma omp taskgroup [task_reduction(id: list )]
```



## Task reductions examples (1)

Reductions with explicit tasks always occur in the environment of a taskgroup (explicit if not implicit), which delimits the scope of reduction operation:

```
#pragma omp parallel
#pragma omp single
{
    #pragma omp taskgroup task_reduction(+: sum)
    {
        for (i=0; i< SIZE; i++)
            #pragma omp task firstprivate(i) in_reduction(+: sum)
            sum += X[i];
    }
}
```

```
#pragma omp parallel
#pragma omp single
{
    // implicit taskgroup in taskloop construct
    #pragma omp taskloop reduction(+: sum)
    for (i=0; i< SIZE; i++)
        sum += X[i];
}
```



## Task reductions examples (2)

Reductions with explicit tasks always occur in the environment of a taskgroup (explicit if not implicit), which delimits the scope of reduction operation:

```
#pragma omp parallel
#pragma omp single
{
    #pragma omp taskgroup task_reduction(+: sum)
    {
        for (i=0; i< SIZE; i++)
            #pragma omp task firstprivate(i) in_reduction(+: sum)
            sum += X[i];

        #pragma omp taskloop in_reduction(+: sum)
        for (i=0; i< SIZE; i++)
            sum += X[i];
    }
}
```



# Parallelism (PAR)

## Short tutorial on OpenMP 5.0 tasking

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