Introduction to OpenMP

Marco Rorro - m.rorro@cineca.it

Neva Bešker - n.besker@cineca.it

CINECA - SuperComputing Applications and Innovation Department

Outline

Disadvantages of MPI

- Each MPI process can only access its local memory
  - The data to be shared must be exchanged with explicit inter-process communications (messages)
  - It is the responsibility of the programmer to design and implement the exchange of data between processes
- You can not adopt a strategy of incremental parallelization
  - The communication structure of the entire program has to be implemented
- The communications have a cost
- It is difficult to have a single version of the code for the serial and MPI program
  - Additional variables are needed
  - You need to manage the correspondence between local variables and global data structure

What is OpenMP?

- De-facto standard Application Program Interface (API) to write shared memory parallel applications in C, C++ and Fortran
- Consists of compilers directives, run-time routines and environment variables
- “Open specifications for Multi Processing” maintained by the OpenMP Architecture Review Board (`http://www.openmp.org`)
- The "workers" who do the work in parallel (thread) "cooperate" through shared memory
  - Memory accesses instead of explicit messages
  - "local" model parallelization of the serial code
- It allows an incremental parallelization

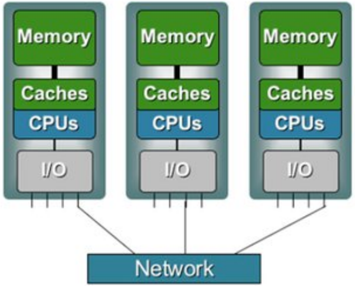
A bit of history

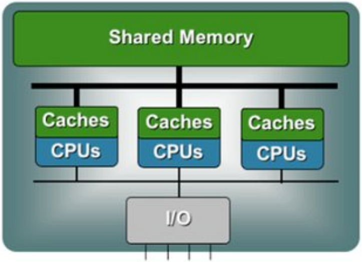
- Born to satisfy the need of unification of proprietary solutions
- The ancient past
  - October 1997 - Fortran version 1.0
  - October 1998 - C/C++ version 1.0
  - November 1999 - Fortran version 1.1 (interpretations)
  - November 2000 - Fortran version 2.0
  - March 2002 - C/C++ version 2.0
  - May 2005 - combined C/C++ and Fortran version 2.5
  - May 2008 - version 3.0 (*task*!)
  - July 2011 - version 3.1
  - July 2013 - version 4.0
- The recent past (with compiler support)
  - November 2015 - version 4.5
- The present and next future
  - November 2018 - version 5.0

Outline

Shared memory architectures

- All processors may access the whole main memory

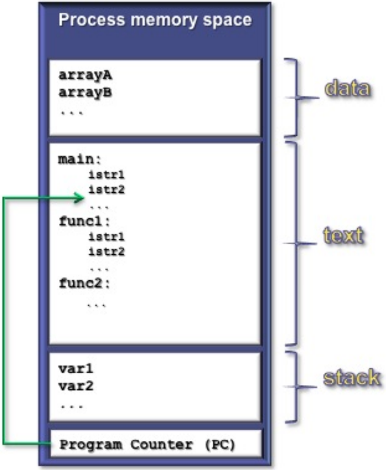




- Non-Uniform Memory Access
  - Memory access time is non-uniform
- Uniform Memory Access
  - Memory access time is uniform

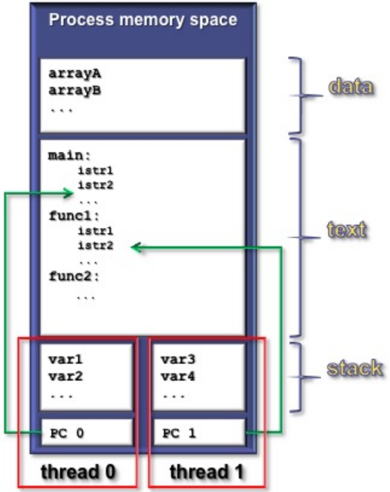
Process and thread

- A process is an instance of a computer program
- Some information included in a process are:
  - Text
    - Machine code
  - Data
    - Global variables
  - Stack
    - Local variables
  - Program counter (PC)
    - A pointer to the istruction to be executed



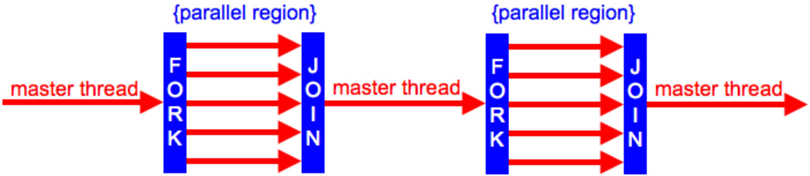
Multi-threading

- The process contains several concurrent execution flows (threads)
  - Each thread has its own program counter (PC)
  - Each thread has its own private stack (variables local to the thread)
  - The instructions executed by a thread can access:
    - the process global memory (data)
    - the thread local stack



Outline

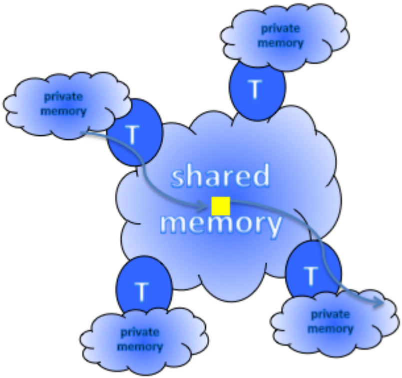
The OpenMP execution model



- The Fork & Join Model
  - Each OpenMP program begins to execute with a single thread (Master thread) that runs the program in serial
  - At the beginning of a parallel region the master thread creates a team of threads composed by himself and by a set of other threads
  - The thread team run in parallel the code contained in the parallel region (Single Program Multiple Data model)
  - At the end of the parallel region the thread team ends the execution and only the master thread continues the execution of the (serial) program

The OpenMP memory model

- All threads have access to the same globally shared memory
- Data in private memory is only accessible by the thread owning this memory
- No other thread sees the change(s)
- Data transfer is through shared memory and is completely transparent to the application



Outline

Directives

- Sintax:
  - in C/C++:
    `#pragma omp direttiva`
  - in Fortran:
    `!$omp direttiva`
  - in Fortran (fixed format):
    `c$omp direttiva`

- Mark a block of code
- Specify to the compiler how to run in parallel the code block
- The serial code "coexists" with the parallel code
  - A serial compilation ignore the directives
  - A compilation with OpenMP support take them into account

Clauses

- Sintax: ***`directive [clause[ clause]...]`***
- Specify additional information to the directives
- Variable handling
  - What are shared among all threads (the default)
  - Which are private to each thread
  - How to initialize the private ones
  - Which is the default
- Execution control
  - How many threads in the team
  - How to distribute the work
- ATTENTION: may alter code semantics
  - The code can be corrected in serial but not in parallell or vice versa

Enviroment variables

- **`OMP_NUM_THREADS`**: sets number of threads
- **`OMP_STACKSIZE "size [B|K|M|G]"`**: size of the stack for threads
- **`OMP_DYNAMIC {TRUE|FALSE}`**: dynamic thread adjustment
- **`OMP_SCHEDULE "schedule[,chunk]"`**: iteration scheduling scheme
- **`OMP_PROC_BIND {TRUE|FALSE}`**: bound threads to processors
- **`OMP_NESTED {TRUE|FALSE}`**: nested parallelism
- ...
- To set them
  - In csh/tcsh: **`setenv OMP_NUM_THREADS 4`**
  - In sh/bash: **`export OMP_NUM_THREADS=4`**

Runtime functions

- Query/specify some specific feature or setting
  - **omp_get_thread_num()**: get thread ID (0 for master thread)
  - **omp_get_num_threads()**: get number of threads in the team
  - **omp_set_num_threads(int n)**: set number of threads
  - ...
- Allow you to manage fine-grained access (lock)
  - **omp_init_lock(lock_var)**: initialize the OpenMP lock variable **lock_var** of type **omp_lock_t**
  - ...
- Timing functions
  - **omp_get_wtime()**: returns elapsed wallclock time
  - **omp_get_wtick()**: returns timer precision
- Functions interface:
  - C/C++: **#include <omp.h>**
  - Fortran: **use omp_lib** (or **include 'omp_lib.h'**)

Conditional compilation

- To avoid dependency on OpenMP libraries you can use pre-processing directives
  - and the preprocessor macro **`_OPENMP`** predefined by the standard
  - C preprocessing directives can be used in Fortran too as well **`!$`** in free form and old style fixed form **`*$`** and **`c$`**

C/C++

```
#ifdef _OPENMP
printf("Compiled with OpenMP support:%d",_OPENMP);
#else
printf("Compiled for serial execution.");
#endif
```

Fortran

```
!$ print *,"Compiled with OpenMP support",_OPENMP
```

Compiling and linking

- The compilers that support OpenMP interpret the directives only if they are invoked with a compiler option (switch)
  - GNU: **`-fopenmp`** for Linux, Solaris, AIX, MacOSX, Windows.
  - IBM: **`-qsmp=omp`** for Windows, AIX and Linux.
  - Sun: **`-xopenmp`** for Solaris and Linux.
  - Intel: **`-openmp`** on Linux or Mac, or **`-Qopenmp`** on Windows
  - PGI: **`-mp`**
- Most of compilers emit useful information enabling extra warning or report options

Outline

`parallel` construct

- It is the main construct of OpenMP it creates a parallel region
  - A construct is the lexical extent to which an executable directive applies
  - A region is the dynamic extent to which an executable directive applies
  - A parallel region is a block of code executed by all threads in the team

C/C++

```
#pragma omp parallel
{
// some work to execute in parallel
} // end of the parallel region (implied barrier)
```

Fortran

```
!$omp parallel
!  some code to execute in parallel
!$omp end parallel
```

Hello world!

C

```
#include <stdio.h>
int main()
{
#pragma omp parallel
   {
      printf("Hello world!\n");
   }
   return 0;
}
```

Fortran

```
Program Hello
!$omp parallel
      print *, "Hello world!"
!$omp end parallel
end program Hello
```

`shared` and `private` variables

- Inside a parallel region, the variables of the serial program can be essentially **`shared`** or **`private`**
  - **`shared`**: there is only one istance of the data
    - Data is accessible by all threads in the team
    - Threads can read and write the data simultaneously
    - All threads access the same address space
  - **`private`**: each thread has a copy of the data
    - No other thread can access this data
    - Changes are only visible to the thread owning the data
    - Valuse are undefined on entry and exit

- Variable are shared by default but with the clause **`default(none)`**
  - No implicit default, have to scope all variables explicitily

Data races & `critical` construct

- A data race is when two or more threads access the same(=shared) memory location
  - Asyncronously and
  - Without holding any common exclusive locks and
  - At least one of the accesses is a write/store
- In this case the resulting values are undefined

- The block of code inside a **`critical`** construct is executed by only one thread at time
- It is a syncronization to avoid simultaneous access to shared data

It could be enough ...

C

```c
sum = 0;
#pragma omp parallel private(i, MyThreadID)
{
   ThreadID = omp_get_thread_num(); NumThreads = omp_get_num_threads();
   int psum = 0;
   for (i=ThreadID*N/NumThreads;i<(ThreadID+1)*N/NumThreads;i++)
     psum +=x[i];
#pragma omp critical
sum +=psum;
}
```

Fortran

```fortran
sum = 0
!$omp parallel private(i, MyThreadID, psum)
MyThreadID = omp_get_thread_num(); NumThreads = omp_get_num_threads()
psum =0
do i=MyThreadID*N/NumThreads+1, min((MyThreadID+1)*N/NumThreads,N)
  psum = psum + x(i)
end do
!$omp critical
  sum = sum + psum;
!$omp end critical
!$omp end parallel
```

but life is easier

- Essentially for a parallelization could be enough:
  - the **`parallel`** construct
  - the **`critical`** construct
  - the **`omp_get_thread_num()`** function
  - and the **`omp_get_num_threads()`** function
- But we need to distribute the serial work among threads
- And doing it by hand is tiring
- The worksharing constructs automate the process

Outline

Worksharing construct

- A worksharing construct distributes the execution of the associated parallel region over the threads that must encounter it
- A worksharing region has no barrier on entry; however, an implied barrier exists at the end of the worksharing region
- If a **`nowait`** clause is present, an implementation may omit the barrier at the end of the worksharing region
- The OpenMP API defines the following worksharing constructs:
  - **`for`**/**`do`** loop construct
  - **`sections`** construct
  - **`single`** construct
  - **`workshare`** contruct (only Fortran)

Outline

Loop construct

- The iterations of the loop are distributed over the threads that already exist in the team
- The iteration variable of the loop is made private by default
- The inner loop are executed sequentially by each thread
- Beware to the data-sharing attribute of the inner loop iteration variables
  - In Fortran are private by defaut
  - In C/C++ no

- Requirements for Loop Parallelization:
  - **no dependencies** between loop indicies;

Loop construct syntax

C/C++

```
#pragma omp for [clauses]
  for(i=0; i<n; i++)
  {  ... }
```

Fortran

```
!$omp do [clauses]
  do i = 1, n
    ...
  end do
[!$omp end do [nowait] ]
```

- Random access iterators are supported too

C++

```
#pragma omp for [clauses]
  for(i=v.begin(); i < v.end(); i++)
  { ... }
```

Loop construct example

C

```
int main ()
{
   int i, n=10;
   int a[n], b[n], c[n];
   ...
#pragma omp parallel
   {
   #pragma omp for
      for (i=0; i<n; i++)
         {
            a[i] = b[i] = i;
            c[i] = 0;
         }
   #pragma omp for
      for (i=0; i<n; i++)
         c[i] = a[i] + b[i];
   }
   ...
```

Loop construct example

Fortran

```
Program doexample
integer, parameter:: n=10
integer:: i, a(n),b(n),c(n)
!$omp parallel
!$omp do
do i=1, n
   a(i) = i
   b(i) = i
   c(i) = 0
end do
!$omp end do
!$omp do
do i=1, n
   c(i) = a(i) + b(i);
end do
!$omp end do
!$omp end parallel
...
```

Loop collapse

- Allows parallelization of perfectly nested loops
- The **collapse** clause on **for**/**do** loop indicates how many loops should be collapsed
- Compiler forms a single loop and then parallelizes it

C/C++

```
#pragma omp for collapse(2) private(j)
for (i=0; i<nx; i++)
   for (j=0; j<ny; j++)
      ...
```

Fortran

```
!$omp do collapse(2)
do j=1, ny
   do i=i,nx
   ...
```

The `schedule` clause

- `schedule(static|dynamic|guided|auto[,chunk])` specifies how iterations of the associated loops are divided into contiguous non-empty subsets, called chunks, and how these chunks are distributed among threads of the team.

C/C++

```
#pragma omp for \
schedule(kind [,chunk])
```

Fortran

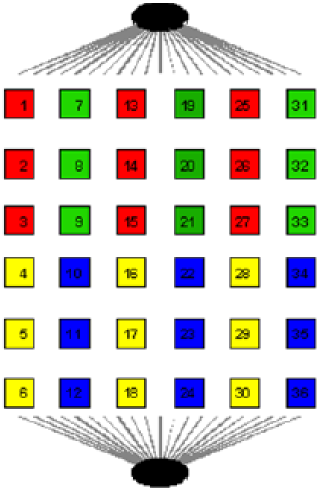
```
!$omp do &
!$omp schedule(kind [,chunk])
```

- Note continuation line

`static` scheduling

- Iterations are divided into chunks of size **`chunk`**, and the chunks are assigned to the threads in the team in a round-robin fashion in the order of the thread number
- It is the default schedule and the default **`chunk`** is approximately $N_{iter}/N_{threads}$
- For example:

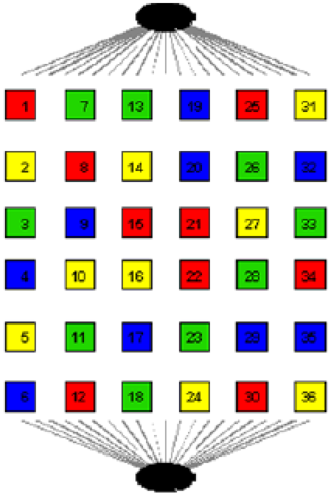
```
!$omp parallel do &
!$omp schedule(static,3)
```



`dynamic` scheduling

- Iterations are distributed to threads in the team in chunks as the threads request them. Each thread executes a **`chunk`** of iterations, then requests another **`chunk`**, until no chunks remain to be distributed.
- The default **`chunk`** is 1
- For example:

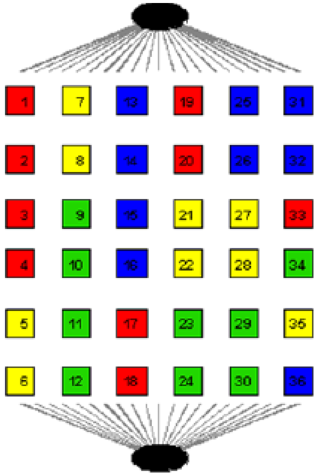
```
!$omp parallel do &
!$omp schedule(dynamic,1)
```



`guided` scheduling

- Iterations are assigned to threads in the team in chunks as the executing threads request them. Each thread executes a chunk of iterations, then requests another chunk, until no chunks remain to be assigned. The chunk decrease to **`chunk`**
- The default value of **`chunk`** is 1
- For example:

```
!$omp parallel do &
!$omp schedule(guided,1)
```



`runtime` and `auto` scheduling

- **`runtime`**: iteration scheduling scheme is set at runtime through the enviroment variable **`OMP_SCHEDULE`**
  - For example:
    ```
    !$omp parallel do &
    !$omp schedule(runtime)
    ```
  - the scheduling scheme can be modified without recompiling the program changing the environment variable **`OMP_SCHEDULE`**, for example: **`setenv OMP_SCHEDULE "dynamic,50"`**
  - Only useful for experimental purposes during the parallelization
- **`auto`**: the decision regarding scheduling is delegated to the compiler and/or runtime system

Scheduling experiment

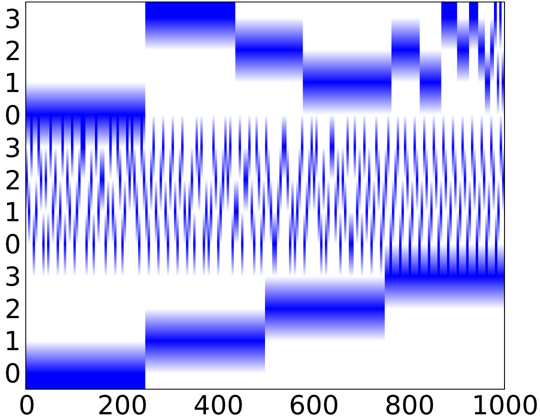


Figure: Different scheduling for a 1000 iterations loop with 4 threads: guided (top), dynamic (middle), static (bottom)

Outline

sections construct

C/C++

```
#pragma omp sections [clauses]
{
  #pragma omp section
  { structured block }
  #pragma omp section
  { structured block }
  ...

}
```

Fortran

```
!$omp sections [clauses]
!$omp section
! structured block
!$omp end section
!$omp section
! structured block
!$omp end section
!...
!$omp end sections
```

- It is a worksharing construct to distribute structured block of code among threads in the team
  - Each thread receive a **section**
  - When a thread has finished executing its section, it receives another **section**
  - If there are none other **section** to execute, threads wait others end up

single construct

C/C++

```
#pragma omp single [private][firstprivate][copyprivate][nowait]
{ structured block }
```

Fortran

```
!$omp single [private][firstprivate]
! structured block
!$omp end single [copyprivate][nowait]
```

- It is a worksharing construct
- The first thread that reaches it executes the associated block
- The other threads in the team wait at the implicit barrier at the end of the construct unless a `nowait` clause is specified

The Fortran `workshare` construct

Fortran

```
!$omp workshare
! structured block
!$omp end workshare [nowait]
```

- The structured block enclosed in the **`workshare`** construct is divided into units of work that are then assigned to the thread such that each unit is executed only once by one thread
- It is only supported in Fortran in order to parallelize the array syntax

Outline

Data-sharing attributes

- In a **`parallel`** construct the data-sharing attributes are *implicitily determined* by the **`default`** clause, if present
    - if no **`default`** clause is present are shared
- Certain variable have a *predetermined* data-sharing attributes
    - Variables with automatic storage duration that are declared in a scope inside a construct are private
    - Objects with dynamic storage duration are shared
    - The loop iteration variable(s) in the associated for-loop(s) of a **`for`** construct is (are) private
    - A loop iteration variable for a sequential loop in a **`parallel`** construct is private in the innermost such construct that encloses the loop (only Fortran)
    - Variables with static storage duration that are declared in a scope inside the construct are shared
    - ...

Data-sharing attributes clauses

- *Explicitly determined* data-sharing attributes are those that are referenced in a given construct and are listed in a data-sharing attribute clause
  - **`shared(list)`**: there is only one istance of the objects in the list accessible by all threads in the team
  - **`private(list)`**: each threads has a copy of the variables in the list
  - **`firstprivate(list)`**: same as **`private`** but all variables in the list are initialized with the value of the original object had before entering the parallel construct
  - **`lastprivate(list)`**: same as **`private`** but the thread that executes the sequentially last iteration or section updates the value of the objects in the list
- The **`default`** clause set the implicit default
  - **`default(none|shared)`** in C/C++
  - **`default(none|shared|private|firstprivate)`** in Fortran

The `reduction` clause

- With the Data-Sharing attributes clause **`reduction`**(op:list)
- For each list item, a private copy is created in each implicit task
- The local copy is initialized appropriately for the operator (for example, if op is + local variables are initialized to 0)
- After the end of the region, the original list item is updated with the values of the private copies using the specified operator
- Supported operator for a **`reduction`** clause are:
  - C: **`+, *, -, &, |, ^, &&, ||`** **`max`** e **`min`**
  - Fortran: **`+, *, -, .and., .or., .eqv., .neqv., max, min, iand, ior, ieor`**
- Reduction variables must be shared variables
- The **`reduction`** clause is valid on **`parallel`**, **`for`**/**`do`** loop and **`sections`** constructs

`reduction` example

C/C++

```
#pragma omp parallel for reduction(+:sum)
for (i=0; i<n; i++)
  sum += x[i];
```

Fortran

```
!$omp parallel do reduction(+:sum)
do i=1, n
  sum = sum + x(i)
end do
!$omp end parallel do
```

- Yes, worksharing constructs can be combined with **`parallel`**
- Beware that the value of a reduction is undefined from the moment the first thread reaches the clause till the operation is completed

Summer School on PARALLEL COMPUTING

Outline

CINECA

Outline

`barrier` construct and `nowait`

- In a parallel region threads proceed asynchronously
- Until they do not encounter a barrier
  - At the barrier all threads wait and only continue when all threads have reached the barrier
  - After a barrier is guaranteed that ALL the code above has been executed
- Explicit barrier
  - **`#pragma omp barrier`** in C/C++
  - **`!$omp barrier`** in Fortran
- Implicit barrier
  - At the end of the worksharing construct
  - Some times are not necessary, and would cause slowdowns
  - Can be removed with the clause **`nowait`**
  - In C/C++, it is one of the clauses on the pragma
  - In Fortran, it is appended at the closing part of the construct

Outline

`atomic` construct

- The **`atomic`** construct applies only to statements that update the value of a variable
  - Ensures that no other thread updates the variable between reading and writing
- The allowed instructions differ between Fortran and C/C++
  - Refer to the OpenMP specifications
- It is a special lightweight form of a **`critical`**
  - Only read/write are serialized, and only if two or more threads access the same memory address

C/C++

```
#pragma omp atomic [clause]
  <statement>
```

Fortran

```
!$omp atomic [clause]
  <statement>
```

atomic Examples

C/C++

```
#pragma omp atomic update
x += n*mass; // default update

#pragma omp atomic read
v = x; // read atomically

#pragma omp atomic write
x = n*mass; write atomically

#pragma omp atomic capture
v = x++; // capture x in v and
         // update x atomically
```

Fortran

```
!$omp atomic update
x = x + n*mass // default
update

!$omp atomic read
v = x // read atomically

!$omp atomic write
x = n*mass write atomically

!$omp atomic capture
v = x     // capture x in v and
x = x+1   // update x atomical
!$omp end atomic
```

master construct

C/C++

```
#pragma omp master
  {<code-block>}
```

Fortran

```
!$omp master
  <code-block>
!$omp end master
```

- Only the master thread executes the associated code block
- There is no implied barrier on entry or exit!

The `threadprivate` directive

C/C++

```
#pragma omp threadprivate(list)
```

Fortran

```
!$omp threadprivate(list)
```

- It is a declarative directive
- It is used to create private copies of
  - *file-scope*, *namespace-scope* or `static` variables in C/C++
  - `common` block or module variables in Fortran
- Follows the variable declaration in the same program unit
- Initial data is undefined, unless the `copyin` clause is used

Orphaning

- The OpenMP specification does not restrict worksharing construct and syncronization directives to be within the lexical extent of a parallel region. These directives can be orphaned
- That is, they can appear outside the lexical extent of a parallel region
- They will be ignored if called from a serial region
- but data-sharing attributes will be applied

Outline

Task parallelism

- Main addition to OpenMP 3.0 enhanced in 3.1 and 4.0
- Allow to parallelize irregular problems
  - Unbounded loop
  - Recursive algorithms
  - Producer/consumer schemes
  - Multiblock grids, Adaptive Mesh Refinement
  - ...

Pointer chasing in OpenMP 2.5

C/C++

```
p = head;
while ( p ) {

   process(p);
p = p->next;
}
```

Fortran

```
p = head
do while ( associated( p ) )

   call process(p)
p => p%next
end do
```

- Trasformation to a “canonical” loop can be very labour-intensive/expensive
- The main drawback of the `single nowait` solution is that it is not composable
- Recall that all worksharing construct can not be nested

Pointer chasing in OpenMP 2.5

C/C++

```
#pragma omp parallel private(p)
   p = head;
   while ( p ) {
   #pragma omp single nowait
      process(p);
   p = p->next;
   }
```

Fortran

```
!$omp parallel private(p)
   p = head
   do while ( associated( p ) )
   !$omp single nowait
      call process(p)
   p => p%next
   end do
```

- Trasformation to a “canonical” loop can be very labour-intensive/expensive
- The main drawback of the `single nowait` solution is that it is not composable
- Recall that all worksharing construct can not be nested

Tree traversal in OpenMP 2.5

C/C++

```
void preorder (node *p) {
 process(p->data);





   if (p->left)
    preorder(p->left);

   if (p->right)
    preorder(p->right);

}
```

Fortran

```
recursive subroutine preorder(p)
 type(node), pointer :: p
 call process(p%data)





   if (associated(p%left))
    call preorder(p%left)
   end if

   if (associated(p%right))
    call preorder(p%right)
   end if

end subroutine preorder
```

- You need to set `OMP_NESTED` to true, but stressing nested parallelism so much is not a good idea ...

Tree traversal in OpenMP 2.5

C/C++

```
void preorder (node *p) {
 process(p->data);
 #pragma omp parallel sections \
  num_threads(2)
 {
  #pragma omp section
  if (p->left)
   preorder(p->left);
  #pragma omp section
  if (p->right)
   preorder(p->right);
 }
}
```

Fortran

```
recursive subroutine preorder(p)
 type(node), pointer :: p
 call process(p%data)
 !$omp parallel sections
 !$omp num_threads(2)
  !$omp section
  if (associated(p%left))
   call preorder(p%left)
  end if
  !$omp section
  if (associated(p%right))
   call preorder(p%right)
  end if
 !$omp end sections
end subroutine preorder
```

- You need to set **`OMP_NESTED`** to true, but stressing nested parallelism so much is not a good idea ...

First & foremost tasking construct

C/C++

```
#pragma omp parallel [clauses]
{
   <structured block>
}
```

Fortran

```
!$omp parallel [clauses]
   <structured block>
!$omp end parallel
```

- Creates both threads and tasks
- These tasks are “implicit”
- Each one is immediately executed by one thread
- Each of them is tied to the assigned thread

New tasking construct

C/C++

```
#pragma omp task [clauses]
{
  <structured block>
}
```

Fortran

```
!$omp task [clauses]
   <structured block>
!$omp end task
```

- Immediately creates a new task but no a new thread
- This task is “explicit”
- It will be executed by a thread in the current team
- It can be deferred until a thread is available to execute
- The data environment is built at creation time
  - Variables inherited their data-sharing attributes but
  - **`private`** variables become **`firstprivate`**

Pointer chasing using task

C/C++

```
#pragma omp parallel private(p)
   #pragma omp single
   {
      p = head;
      while ( p ) {
      #pragma omp task
         process(p);
      p = p->next;
   }
}
```

Fortran

```
!$omp parallel private(p)
   !$omp single
      p = head
      do while (associated(p))
         !$omp task
            call process(p)
         !$omp end task
         p => p%next
      end do
   !$omp end single
!$omp end parallel
```

- One threads creates task
  - Packages code and data environment
  - Then reaches the implicit barrier and starts to execute the task
- The other threads reaches straight the implicit barrier and start to execute task

Load balancing on lists with task

C/C++

```
#pragma omp parallel
{
   #pragma omp for private(p)
   for (i=0; i<num_lists; i++) {
      p = head[i];
      while ( p ) {
      #pragma omp task
         process(p);
      p = p->next;
      }
   }
}
```

Fortran

```
!$omp parallel
   !$omp do private(p)
   do i=1,num_lists
      p => head[i]
      do while (associated(p))
         !$omp task
            call process(p)
         !$omp end task
         p => p%next
      end do
   end do
   !$omp end do
!$omp end parallel
```

- Assign one list per thread could be unbalanced
- Multiple threads create task
- All team cooperates executing them

Tree traversal with task

C/C++

```
void preorder (node *p) {
 process(p->data);
 if (p->left)
 #pragma omp task
   preorder(p->left);
 if (p->right)
 #pragma omp task
   preorder(p->right);
}
```

Fortran

```
recursive subroutine preorder(p)
 type(node), pointer :: p
 call process(p%data)
  if (associated(p%left))
  !$omp task
   call preorder(p%left)
  !$omp end task
  end if
  if (associated(p%right))
  !$omp task
   call preorder(p%right)
  !$omp end task
  end if
end subroutine preorder
```

- Task are composable
- It isn't a worksharing construct

Postorder tree traversal with task

C/C++

```
void postorder (node *p) {
 if (p->left)
 #pragma omp task
   postorder(p->left);
 if (p->right)
 #pragma omp task
   postorder(p->right);
 #pragma omp taskwait
 process(p->data);
}
```

Fortran

```
recursive subroutine postorder(p)
 type(node), pointer :: p
  if (associated(p%left))
  !$omp omp task}
   call postorder(p%left)
  !$omp end task
  end if
  if (associated(p%right))
  !$omp omp task
   call postorder(p%right)
  !$omp end task
  end if
  !$omp taskwait
  call process(p%data)
end subroutine postorder
```

- **`taskwait`** suspend parent task until children tasks complete

Outline

Conclusions

- What we left out
  - SIMD constructs: `simd` and `declare simd`
  - Device constructs: `target data`, `teams`, `distribute`, ...
  - UDR directive: `declare reduction`
  - Cancellation constructs: `cancel` and `cancellation point`
  - and many other
- Where to find more
  - In the OpenMP specification that can be downloaded from `www.openmp.org`
  - The same web site make available further resources: forum, tutorial, news, etc.
- Credits
  - Several people of the SCAI staff
  - Many people involved on OpenMP: R. van der Pas, A. Duran, B. de Supinski, T. Mattson, L. Meadows, ...