Parallel Computing &
OpenMP – Parallel Regions

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2023-2024 @ Università di Trieste

OpenMP Outline

Parallel Regions

Parallel Loops

NUMA AWARENESS

Parallel Regions

As we have seen in the introduction, the OpenMP’s running model if *fork-join* (i.e. forking a pool of threads to perform parallel work and to re-join them to the father process a the end of the parallel work).

What we call “parallel work” then happens in “parallel regions” of the code.

How do we define a parallel region in OpenMP? Where do the threads “live” ?

That is what we discuss in the next slides.

Parallel Regions

The following are the OMP constructs that can be used to create parallel regions:

```
#pragma omp parallel _some_clauses_here_
single-line-here
```

A parallel region can be as short as a single line

```
#pragma omp parallel _some_clauses_here_
{ … }
```

There are no limits on the size of the code included within {..}.

```
#pragma omp parallel for _some_clauses_here_
{ … }
```

The specific construct about `for` loops

```
#pragma omp sections _some_clauses_here_
{ … }
```

A more general work-sharing construct

```
#pragma omp task _some_clauses_here_
{ … }
```

This allows task-based parallelism

The region starts at the opening { brace and ends at the closing } one.
An implicit synchronization barrier is present at the end of the region (*).

However, for efficiency reasons, it may be, and usually it is, that the threads are not created/killed at the begin/end of each region; instead, they are created at the begin of the run and kept sleeping outside of the parallel regions.

(*) we'll see the details about synchronization later on

The threads factory

When you create a parallel region, through an OpenMP directive, a pool of threads is created.
Each one receives an ID, ranging from 0 to *n*-1, where *n* is the number of threads.

Their stack and IP are separated from the others' ones and from the father-process' ones.

Can we check that?
What is the fate of the creating process (thread) ?

```
int    i;

register unsigned long long base_of_stack asm("rbp");
register unsigned long long top_of_stack asm("rsp");

 printf( "\nmain thread (pid: %d, tid: %d) data:\n"
         "base of stack is: %p\n"
         "top of stack is : %p\n"
         "&i is           : %p\n"
         "   rbp - &i     : %td\n"
         "   &i - rsp     : %td\n"
         "\n\n",
         getpid(), syscall(SYS_gettid),
         (void*)base_of_stack,
         (void*)top_of_stack,
         &i,
         (void*)base_of_stack - (void*)&i,
         (void*)&i - (void*)top_of_stack );

#pragma omp parallel private(i)
  {
    int me = omp_get_thread_num();
    unsigned long long my_stackbase;
    __asm__("mov %%rbp,%0" : "=mr" (my_stackbase));

    printf( "\tthread (tid: %ld) nr %d:\n"
                     "\t\tmy base of stack is %p ( %td from main\'s stack )\n",
                     "\t\tmy i address is %p\n"
                     "\t\t\t%td from my stackbase and %td from main\'s\n",
                     syscall(SYS_gettid), me,
                     (void*)my_stackbase, (void*)base_of_stack - (void*)my_stackbase,
                     &i, (void*)&i - (void*)my_stackbase,
                     (void*)&i - (void*)base_of_stack);
```

parallel_regions/
00_stack_and_scope.c

The threads factory

serial section

```
main thread (pid: 26291, tid: 26291) data:
base of stack is: 0x7ffe6f51efc0
top of stack is : 0x7ffe6f51ef60
&i is           : 0x7ffe6f51ef7c
   rbp - &i     : 68
   &i - rsp     : 28
```

parallel region

```
thread (tid: 26291) nr 0:
        my base of stack is 0x7ffe6f51eee0 ( 224 from main's stack )
        my i address is 0x7ffe6f51eea0
                -64 from my stackbase and -288 from main's
thread (tid: 26293) nr 2:
        my base of stack is 0x7f7342c82ba0 ( 597747680288 from main's stack )
        my i address is 0x7f7342c82b60
                -64 from my stackbase and -597747680352 from main's
thread (tid: 26294) nr 3:
        my base of stack is 0x7f7342880ba0 ( 597751882784 from main's stack )
        my i address is 0x7f7342880b60
                -64 from my stackbase and -597751882848 from main's
thread (tid: 26292) nr 1:
        my base of stack is 0x7f7343084b20 ( 597743477920 from main's stack )
        my i address is 0x7f7343084ae0
                -64 from my stackbase and -597743477984 from main's
```

`pid` and `tid` are the IDs of processes and threads for the OS.
Here you see that the master thread stops its activity and join the new pool of threads, while maintaining its own `tid`.

- Each thread has its own stack; `thread 0` inherits its own stack, which has grown to host the data relative to OpenMP parallel region;
- the private `i`s are actually in the threads stacks, and so they are at different memory locations than the shared `i`.

parallel_regions/
00_stack_and_scope.c

The threads factory

How large is the stack of each thread? The default value is system dependent.
That is the output of the `00_stack_and_scope` code example: it prints the `BP` and `SP` pointers of each thread. Then, we know how large is the threads' stack at a given moment (only an integer is defined, plus the system's thread structure), and how much memory is reserved for the stack to grow:

```
thread 0: bp @ 0x7ffc6edea2f0, tp @ 0x7ffc6edea280: 112 B
thread 1: bp @ 0x7fa371d18b20, tp @ 0x7fa371d18ab0: 112 B        --> -382202615648 B from top of thread 0
thread 2: bp @ 0x7fa371916ba0, tp @ 0x7fa371916b30: 112 B        --> -4202256 B from top of thread 1
thread 3: bp @ 0x7fa371514ba0, tp @ 0x7fa371514b30: 112 B        --> -4202384 B from top of thread 2

you did not define OMP_STACKSIZE: try to set it and check what happens to the threads' stack pointers
```

In this case, compiled with gcc, it seems that about 4MB are reserved for each thread. The same value holds with pgi, whereas clang seems to reserve 132MB (i.e., the addresses in the virtual space are spaced by 132MB).
However, you can control the size of the threads' stack using the environmental variable `OMP_STACKSIZE`:

```
export OMP_STACKSIZE=N
```

Where `N` is a number, followed by a letter: '`B`', '`K`', '`M`', '`G`' mean bytes, kilobytes, megabytes and gigabytes respectively (if no letter is specified, the number is interpreted as kilobytes).

The threads factory


```
export OMP_STACKSIZE=32K
```

```
thread 0: bp @ 0x7ffd1a2bbc70, tp @ 0x7ffd1a2bbbd0: 160 B
thread 1: bp @ 0x7f18b4be4af0, tp @ 0x7f18b4be4a50: 160 B        --> -980954214624 B from top of thread 0
thread 2: bp @ 0x7f18b4bdab70, tp @ 0x7f18b4bdaad0: 160 B        --> -40672 B from top of thread 1
thread 3: bp @ 0x7f18b4bd0b70, tp @ 0x7f18b4bd0ad0: 160 B        --> -40800 B from top of thread 2

you defined OMP_STACKSIZE as 32K: try to change that value and check what happens to the threads' stack pointers
```

```
export OMP_STACKSIZE=1M
```

```
thread 0: bp @ 0x7ffc6f8b97f0, tp @ 0x7ffc6f8b9750: 160 B
thread 1: bp @ 0x7fd5bf930af0, tp @ 0x7fd5bf930a50: 160 B        --> -166161058912 B from top of thread 0
thread 2: bp @ 0x7fd5bec96b70, tp @ 0x7fd5bec96ad0: 160 B        --> -13213408 B from top of thread 1
thread 3: bp @ 0x7fd5beb94b70, tp @ 0x7fd5beb94ad0: 160 B        --> -1056608 B from top of thread 2

you defined OMP_STACKSIZE as 1M: try to change that value and check what happens to the threads' stack pointers
```

The threads factory

How many threads can be created by a single process?
Also this limit is system-dependent.

On Linux, it depends on the amount of total physical memory: basically, the maximum number of threads is the amount of physical memory divided by the memory amount needed to describe and run a thread, times a factor that accounts for the fact that you don't want all the memory allocated only to make the threads alive.
Within this limit, you can change the behaviour of your OpenMP program by using the env variable OMP_THREAD_LIMIT.

You can check the OS' limit with

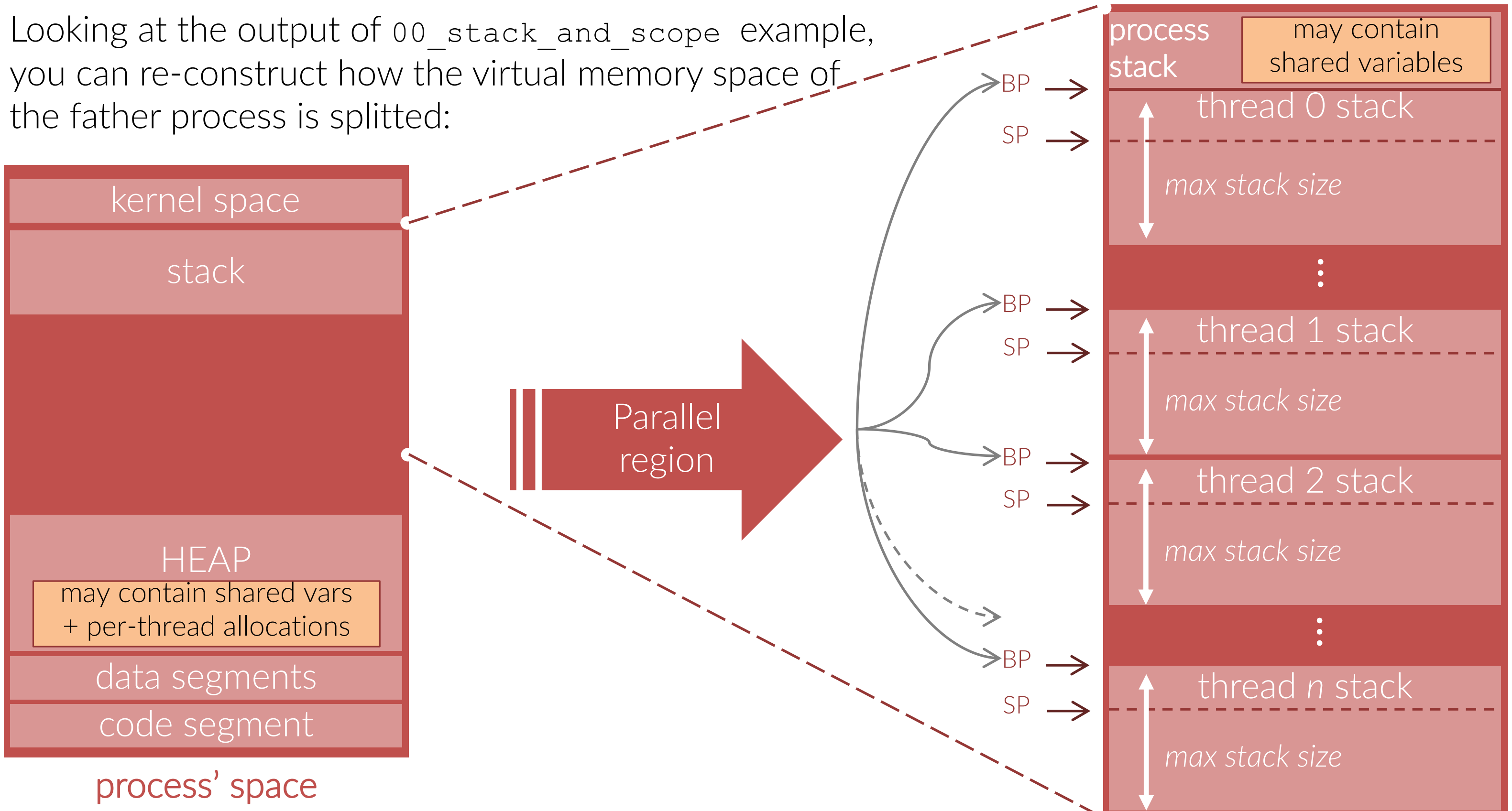
```
cat /proc/sys/kernel/threads-max
```

or by calling the omp library function

```
int omp_get_max_threads()
```

The threads factory

Looking at the output of `00_stack_and_scope` example, you can re-construct how the virtual memory space of the father process is splitted:



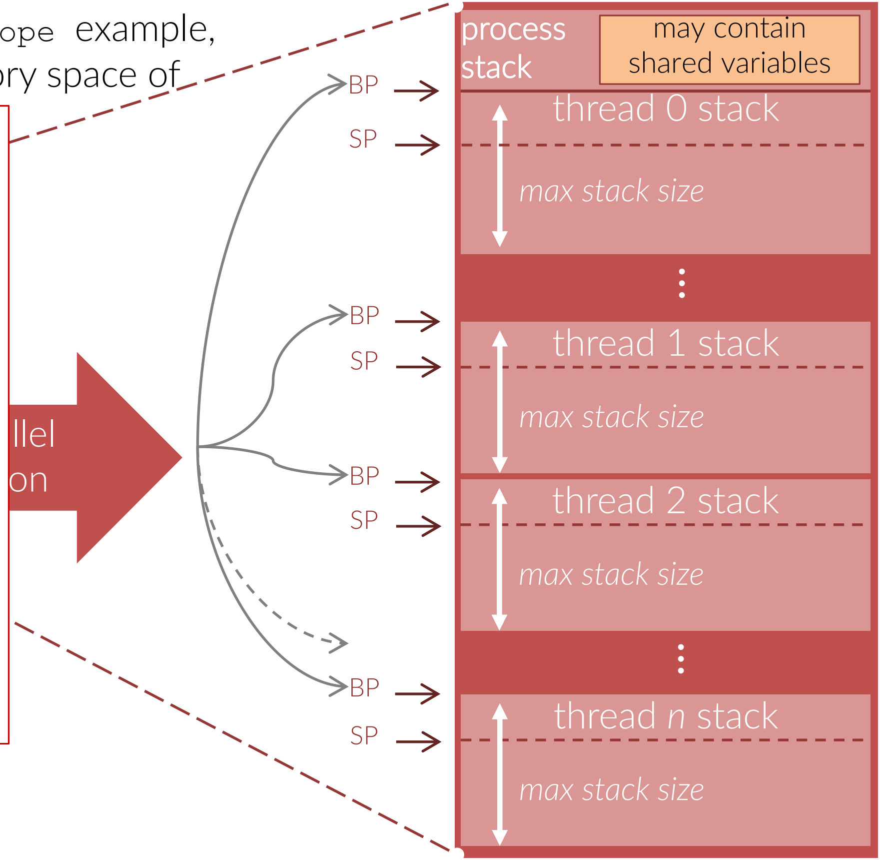
The threads factory

Looking at the output of `00_stack_and_scope` example, you can re-construct how the virtual memory space of

Be aware:

When the threads are created, the space needed for their stack is also allocated. If that space is quite large, you may run out of memory.

Conversely, if the stack is not large enough, you may incur into `seg fault` error (due to lack of memory in the stack)

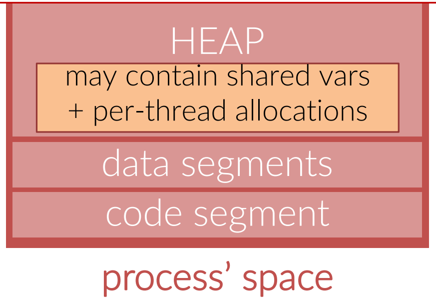


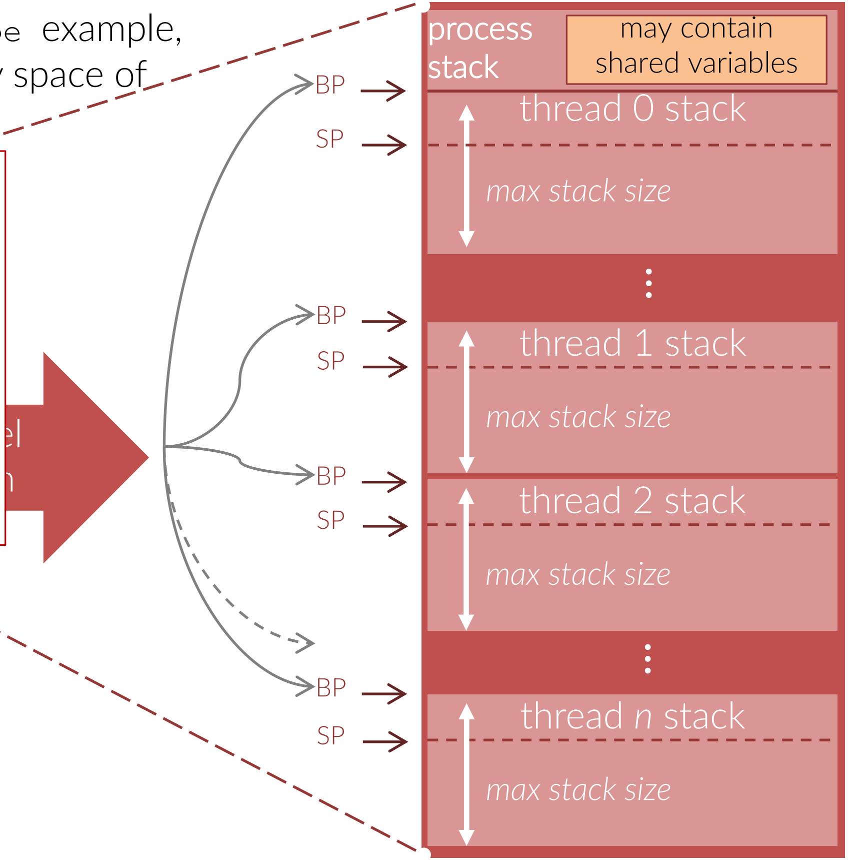
process' space

The threads factory

Looking at the output of `00_stack_and_scope` example, you can re-construct how the virtual memory space of the father process is splitted:

In general, this advocates for the same wise variables placement either on the stack or on the heap that is valid for single-thread application





Resumé of what we have learnt on threads in omp:

- each thread has a separated stack, defined by its own frame (i.e. BP and SP values)
- "private" variables live in the stack of each thread, i.e. in a parallel region we address separated variables(*) for each thread even if we are using the same name in the code
- the stacks of the threads have also a maximum size, and in fact in the process' virtual address space they are placed at a distance that is basically equal to that maximum size
- the default value of that maximum stack size is implementation dependent but can be set using an appropriate environmental variable

(*) reminder: "a variable" is a memory region whose content we interpret in some way (int, double, char, ptr, ..)

Managing the shared/private memory

Let's now start to clarify the meaning of "private" and "shared" memory, and how to specify what variables are either one.

Managing the shared/private memory

```
int     i, j, k;
double *array;

#pragma omp parallel
{
   // i,j,k and array
   // are shared here
  ...
}
```

The basic rule is that everything that is defined in a serial region is inherited as *shared* in a parallel region that originates from the former serial region. *Global* variables are always shared (we'll see and exception).

In this case, `i,j,k` and `array` are all *shared* within the parallel region, meaning that all the threads inside that region can concurrently access them.
To be absolutely clear:
`&i, &j, &k` and `&array` are exactly the same for all the threads.

Managing the shared/private memory

```
int     i, j, k;
double *array;

#pragma omp parallel private(i,k)
{
   // j and array
   // are shared here
   // i and k are unique to each
   // thread, they live in each
   // thread's stack.
   // They are different than
   // the original j and k
  ...
}
```

You can specify that a list of variables(*) that exists in the local stack at the moment of the creation of the parallel region are **`private`** to each thread inside the parallel region.

That means that the needed space will be reserved in the threads' stack to host variables of the same types. As such, those memory regions are *different* than the original ones, although within the parallel region those variables are referred in the source code with the same names.

(*) specified as a comma-sperated list of names

Managing the shared/private memory

```
int     i, j, k;
double *array;
array = (double*)malloc(...);

#pragma omp parallel private(array)
{
   // now array is unique to
   // each thread and it does NOT
   // point to the region pointed
   // by the original array pointer
  ...
}
```

In this case, array is declared as *private*.
As before, it means that in the stack of every thread there will be 8 bytes dedicated to host a variable referred as `array` in the source code that however is different than the original array variable in the serial region.

Then if the code tries to use it to address the memory allocated in the serial region, there will be weird things going on.
(see the example `OpenMP/parallel_regions/00_stack_and_scope.c`)

Managing the shared/private memory

In the following slide, that also addresses you to two example codes, we’ll see a simple example of wrong usage of a de-facto *shared* variable that should have been *private*.

Managing the shared/private memory

returns the ID of the calling thread

```
int nthreads      = 1;
int my_thread_id = 0;

#ifdef _OPENMP
#pragma omp parallel
{
    my_thread_id = omp_get_thread_num();
    #pragma omp master
    nthreads      = omp_get_num_threads();
}
#endif
```

returns the number of threads active in that parallel region

By default rules, variables declared outside a parallel region are *shared*, whereas those declared inside a region are *private*.
Then both `nthreads` and `my_thread_id` are shared.

As a consequence, in this example:
- all threads are writing in `my_thread_id`, in undefined order
- only the master thread is writing in `nthreads`

The value of `my_thread_id` is unpredictable, because it depends on the run-time order by which the threads access it and by each a thread accesses it again to write it.

parallel_regions/
01_simple_pr_wrong.c
02_simple_pr.c

Managing the shared/private memory

The clause `private()` that can be added to the `parallel` directive may generate come confusion.

Let's try to clarify that in the following couple of slides.

Managing the shared/private memory

```
int i;

#pragma omp parallel private(i)
{
   ... using i
}
```

TIPS

This code, perfectly follows the OpenMP standards.
You find several examples around - i.e. shared variables defined as private at the entrance of the parallel regions.

However, *in my opinion*, it's just a relic from old times and a wrong way of thinking and programming.

In fact, "`i`" as used in the parallel region refers to a memory region that is different than the "`i`" in the serial region: as such, this coding style looks only a source of confusion and lacks of cleariness.

I strongly advice you to avoid it.

Managing the shared/private memory


```
int i;
..using i

#pragma omp parallel
{
  int j;
  ..using j
}

..using i
```

TIPS

The effect of the previous code is the same than this one: you have an integer in the stack of each thread, without any need of referring it with the same name.
In general, then, my advice is: if you need a private variable in the parallel region, just define it clearly inside the parallel region.

If a variable is defined in the serial region, it must have a scope and a usage in the serial region.

Some possibile handy exception will be discussed later, like the usage of `firstprivate` or `lastprivate`

Controlling the number of threads

By default the number of threads spawned in a parallel regions is the number of cores available.
However, you can vary that number in several way

- `OMP_NUM_THREADS environmental variable`
- `#pragma omp parallel num_threads(n)`
- ```
  omp_set_num_threads(n);
  #pragma omp parallel
  ```

parallel_regions/
03a_num_of_threads.c
  ```

Controlling the number of threads

By default the number of threads spawned in a parallel regions is the number of cores available.
However, you can vary that number in several way

- `OMP_NUM_THREADS environmental variable`
- `#pragma omp parallel num_threads(n)`
- `omp_set_num_threads(n);`
  `#pragma omp parallel`

That works if `OMP_DYNAMIC` variable is set to `TRUE`, otherwise the number of threads spawned is strictly equal to `OMP_NUM_THREADS`.
This setting can be changed through
`omp_set_dynamic( true )`

parallel_regions/
03a_num_of_threads.c + 03b_num_of_threads.c

The ordering of the threads


```c
#pragma omp parallel
{
    int my_thread_id = omp_get_thread_num();
    printf( "greetings from thread num %d\n",
            my_thread_id );
}
```

The order by which the greetings appear in the output is not deterministic.

In general, unless either you explicitly requires so – and that is possible only for some constructs, or you directly code it, **there is no given order, since the threads are independent entities.**

How would you build-up an enforcement of the order in the parallel region shown here on the left ?

The ordering of the threads

```
int order = 0;

#pragma omp parallel
{
    int myid = omp_get_thread_num();

    #pragma omp critical
    if ( order == myid ) {
       printf( "greetings from thread num %d\n",
               my_thread_id );
     order++; }
}
```

parallel_regions/
04_order_of_threads_wrong.c

The CRITICAL directive defines a region which is executed by all threads but by a single thread at a time. Which starts to sound like an "ordering".

However, although the threads queue up at the begin of the region, no particular order is imposed to that queue. As a consequence, the result is unpredictable, aside the fact that `thread 0` will print the message and increase `order`.
For instance, if `thread 2` is queued immediately after, it will execute the `if` evaluation which will fail (`order` would be equal to 1) and the `thread 2` will not print the message at all.

The ordering of the threads


```
int order = 0;

#pragma omp parallel
{
    int myid = omp_get_thread_num();
    int done = 0

    while (!done) {
    #pragma omp critical
    if ( order == myid ) {
       printf( "greetings from thread num %d\n",
               my_thread_id );
        order++; done=1; } }
}
```

parallel_regions/
05a_order_of_threads.c

In this second implementation, the `while` cycle enforces the threads that fails the if condition to keep trying until the correct order is ensured.

Once a thread has executed the `critical` region, it then exits the `while` and join the implicit synchronization barrier at the end of the parallel region.

A note: without the `critical` directive, this code could work as well on most platform. However, it is still unreliable since it is not guaranteed that each thread complete the region *before* the successive threads enter in it. For instance, the compiler could have been reshuffled the `order++` instruction placing it before the print and so the `thread` *n+1* could enter the region before of the print of the `thread n` and its message could appear as first.

The ordering of the threads

```c
int nthreads = 1;

#pragma omp parallel
{
    int myid = omp_get_thread_num();
   #pragma omp master
    int nthreads = omp_get_num_threads();
   #pragma omp barrier

   #pragma omp for ordered
    for ( int i = 0; i < nthreads; i++ )
      #pragma omp ordered
       printf( "greetings from thread num %d\n",
               my_thread_id );
}
```

In this third implementation, we use the clause `ordered` which force a work-sharing loop to be executed in the order of the loop iteration. `ordered` may also be a stand-alone directive that specifies cross-iteration dependences.

parallel_regions/
05b_order_of_threads.c + 05c_order_of_threads.c

The ordering of the threads

```
int nthreads = 1;

#pragma omp parallel
{
    int myid = omp_get_thread_num();
   #pragma omp master
    int nthreads = omp_get_num_threads();
   #pragma omp barrier

   #pragma omp for ordered
    for ( int i = 0; i < nthreads; i++ )
      #pragma omp ordered
       printf( "greetings from thread num %d\n",
               my_thread_id );
}
```

A note: without the `barrier` directive, it may happen that some threads (potentially all of them) arrive at the worksharing contruct `for` with a wrong value of `nthreads`

parallel_regions/
05b_order_of_threads.c + 05c_order_of_threads.c

The ordering of the threads

```
int nthreads = 1;

#pragma omp parallel
{
    int myid = omp_get_thread_num();
   #pragma omp single
    {
      int nthreads = omp_get_num_threads();
    }

   #pragma omp for ordered
    for ( int i = 0; i < nthreads; i++ )
      #pragma omp ordered
       printf( "greetings from thread num %d\n",
               my_thread_id );
}
```

parallel_regions/
05b_order_of_threads.c + 05c_order_of_threads.c

A note: without the `barrier` directive, it may happen that some threads (potentially all of them) arrive at the worksharing contruct `for` with a wrong value of `nthreads`

That's a case for a single construct, which has an implicit barrier at the end of the code block.

Specializing execution in PR

In a given parallel region not all the time some code block must be executed in parallel.

Some times, we want that just *one* thread executes it, i.e. it is inherently unique, or that just *one* thread *at a time* executes it, i.e. it is inherently serial (even in the middle of a parallel workflow some operations may still be serial).

In the following slides we discuss some handy shortcuts offered by omp to achieve this effects.

Specializing execution in PR

```
#pragma omp parallel
{
    #pragma omp critical
    { code block
    }

    #pragma omp atomic
    assignment instruction

    #pragma omp single
    { code block
    }

    #pragma omp master
    { code block
    }
}
```

The `critical` directive ensures that only a thread at a time executes the block. All the threads will execute it, although in unspecified order.

Like `critical` but limited to the following single line.
The instruction can only be an assignment in the form
x* binop = *expr

Only one among the threads will enter the code block

Only the master thread will enter the code block

Specializing execution in PR

```
#pragma omp parallel
{
    #pragma omp critical
    { code block
    }

    #pragma omp atomic
    assignment instruction

    #pragma omp single
    { code block
    }

    #pragma omp master
    { code block
    }
}
```

A barrier (in the form of queuing) is present at the entry point; no one at the end point, i.e. the threads exiting the region will continue the run.

Synchronization as in **`critical`** region.

Implicit synchronization at *the end*. Only one thread is inside the region, the others are waiting at the end of the region.

No explicit synchronization at all. Only the thread 0 is inside the region, the other ones can be everywhere else.

Specializing execution in PR

TIPS

Rationale of

```
#pragma omp atomic
assignment instruction
```

When you deal with shared variables, ensuring that the workflow maintains the semantic correctness of your code is fundamental.
For instance, the assignment

a += b

(where either `a`, `b` or both are shared) is meaningful only if the value of `a` (or `b`, or both) does not change in the middle of the instruction itself.

In fact, while a single assembly instruction is guaranteed not to be ever interrupted on the fly, we have to take into account that even a single C line translates in several asm instructions. So, the value of a shared variable could have been changed in the middle of that groups of asm instructions, breaking the correctness of the code (*).

To avoid that, it is necessary to "protect" the sensible regions.

An **`atomic`** assignment has, obviously, a much lower overhead than a **`critical`** region and must be preferred in the appropriate cases.

(*) std C and C++ also expose to the programmer a large bunch of atomic instructions

Specializing execution in PR

TIPS

Special clauses for **atomic**

Rationale of

```
#pragma omp atomic
assignment instruction

Clauses:
read, write, update,
capture
```

read	`var = mem`	causes an atomic read of the location designated by *mem* regardless of the native machine word size
write	`mem = var`	causes an atomic write of the location designated by *mem* regardless of the native machine word size
update	`mem++, ++mem,` `mem--, --mem,` `mem binop= expr`	Causes an atomic update of the location designated by *mem* using the designated operator or intrinsic
capture	`val = mem++,` `val = ++mem,` `val = mem--,` `val = --mem,` `val = mem binop= expr` `{val = mem; mem binop= expr}` `{mem binop= expr; val = mem}`	Causes an atomic update of the location designated by *mem* using the designated operator or intrinsic while also capturing the original or final value of the location designated by *x* with respect to the atomic update. The original or final value of the location designated by *mem* is written in the location designated by *val*, depending on the form of the `atomic` construct, structured block, or statements, following the usual language semantics

Specializing execution in PR

TIPS

```
#pragma omp critical
{
   "A" code block
}
#pragma omp critical
{
   "B" code block
}
#pragma omp critical(my_loop)
{
   code block
}
```

Named critical regions

In OpenMP it exists a unique global `critical` section.
Hence, when you define a `critical` section, it is logically considered to be part of the global one.
As a consequence *only one thread can be inside any of the unnamed `critical` sections*, which of course limits the perfomance whn more than one region is present.

However, that can be cured by the *named regions*, defined as the last one in the code snippet here on the left.
In that example, only one thread can be either in region "A" or in region "B": so, if one thread is executing "A", another one is forced to delay entering "B" even it would have been reading for it.

Instead, the named `critical` regions can be executed at the same time (by different threads, of course, and only by one thread at a time).

Specializing execution in PR

TIPS

```
#pragma omp critical
{ …
  some_assignment_to x;
  …
}

#pragma omp atomic
x op= value
```

`critical` *and* **`atomic`**

Consider that by design `atomic` protects *memory regions*, while `critical` protects code regions.

Hence they are not mutually exclusive: a thread may be executing the critical region while another may be executing the atomic.

Specializing execution in PR

TIPS

```
#pragma omp single
{ …code block… }
```

```
#pragma omp master
{ …code block… }
```

Is there any difference between using `single` or `master` ?

There obviously is if you're assigning some special workflow to `thread 0`.
If not, the entity of the difference depends on the implementation details.

In general, using `master` requires only a simple test on the thread id, while using `single` requires more synchronization (the `openmp` infrastructure has to keep track about what thread is in the region and so on).

In general, if you have some insight about the fact that the workload before that point may be systematically unbalanced, so that some thread will likely arrive first, using `single` is ok.
Otherwise, it may be better to use `master`.

Work assignment

So far we have not seen any way to assign different work to different threads (but for the `single` and `master` directives).

However, to be truly in parallel most of the times we want that:

1. either the threads perform the *same operations* on *different data* (so that we perform a domain decomposition)
2. or that different threads perform *different operations* on data (so that we perform a functional decomposition)

A very common work-sharing construct with domain decomposition is the for loop, which we treat in the next lectures.
An advanced way to achieve wither functional decomposition and/or domain decomposition is the tasks-creation mechanisms, that we will also see in detail.

In general, you may achieve 1) and/or 2) by hands coding different workflows that depend on the threads' id, as in the following example.

Work assignment

Inside a parallel region, the work can be assigned to each threads (actually, that's why PR are created..):

```
…
results[0] = heavy_work_0();
results[1] = heavy_work_1();
results[2] = heavy_work_2();
…
```

```
#pragma omp parallel
{
    if( myid % 3 == 0)
        result = heavy_work_0( );
    else if ( myid % 3 == 1 )
        result = heavy_work_1( );
    else if ( myid % 3 == 2 )
        result = heavy_work_2( );

    if ( myid < 3 )
        results[myid] = result;
}
```

dynamic extent

parallel_region/
06_assign_work.c

run with a second
argument >0 to check
about it

parallel_region/
06a_assign_work.c

Conditional creation of PR

It is possible to spawn a parallel region only if some conditions are met:

- `#pragma omp parallel if(` *`any valid C expression`* `)`

```
#pragma omp parallel if( amount_of_work > high )
{
    if( myid % 3 == 0)
        result = heavy_work_0( );
    else if ( myid % 3 == 1 )
        result = heavy_work_1( );
    else if ( myid % 3 == 2 )
        result = heavy_work_2( );

    if ( myid < 3 )
        results[myid] = result;
}
```

If the condition is not fulfilled, the threads are not created and only the master thread will execute the code block.

parallel_region/
06a_assign_work.c

if the first argument, that determines the amount of work, is ≤10, the parallel region is **not** created

Conditional creation of PR

TIPS

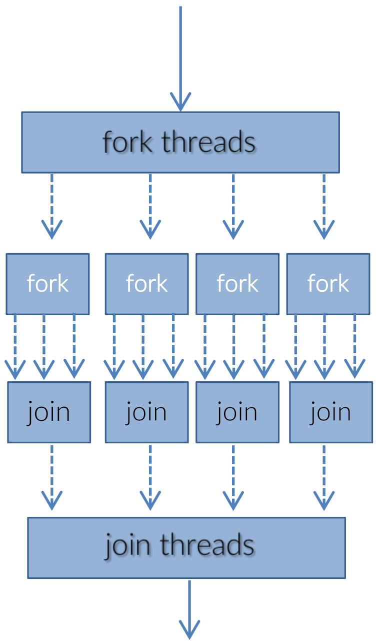
What is this useful for?

The overhead of the creation of a parallel region is of the order of ~10 μseconds (that figure is dependent on the system, the compiler, the number of threads,…).

Then, you may want to create a parallel region (i.e. to spawn more threads) only if the serial execution of that code section is at least several times this overhead.

Nested Parallel Regions

NESTED PARALLELISM



Nested parallelism is explicitly_permitted in OpenMP. Whether it is *active* or not, depends on the value of some environmental variables:

OMP_NESTED=<TRUE | FALSE> (*) default value is FALSE
OMP_NUM_THREADS=N_0<,N_1, … >
OMP_MAX_ACTIVE_LEVELS=*n*

Which you can change by calling the appropriate OMP_ functions

omp_get_nested(), omp_set_nested(*cond*)

(*)OMP_NESTED is deprecated in new OpenMP 5.0. You should use only OMP_MAX_ACTIVE_LEVELS and OMP_NUM_THREADS. OMP_NESTED is in fact redundant. However, at the moment of writing the compilers still support OMP_NESTED.

07_simple_nested_regions.c

Managing the shared/private memory

directives for parallel regions	#pragma omp parallel directive
work-sharing constructs	#pragma omp for #pragma omp section #pragma omp task
data attributes	shared, private, firstprivate, lastprivate, copyin, copyprivate, threadprivate clauses
Synchronization	critical, atomic, barrier, ordered, flush, nowait
run-time	Lot of run-time functions and utils omp_set_num_threads(), omp_get_thread_num() ,...

Managing the shared/private memory

data attributes

shared, private, firstprivate, lastprivate, copyin, copyprivate, threadprivate clauses

These clauses, that you can use at the opening of parallel regions and constructs allow a fine tuning about how to manage variables that are shared, i.e. that are formally declared in a serial region of the code.

Managing the shared/private memory

```
int     i, j, k;
double *array;
array = (double*)malloc(...);

#pragma omp parallel
firstprivate(array)
{
   // now array is unique to each thread,
   // BUT each copy is initialized to the
   // value that the original array has
   // at the entry of the parallel region.
   // As such, now array can be used to
   // access the previously allocated
   // memory.
  ...
}
```

If the clause **`firstprivate()`** is used instead, every variable listed is private in the same sense than before, but its value is not randomic but it is **initialized** at the value that the corresponding variable in the serial region has at the moment of entering in the parallel region.

parallel_regions/
09_clauses__firstprivate.c

Managing the shared/private memory

```c
double last_result;

#pragma omp parallel
lastprivate(last_result)
{
  ...
  #pragma omp for
  for( int j = 0; j < some_value; j++ )
    last_result = calculation( j, ...);
  ...
}

other_calculations( last_result, ... );
// at this point, last_result has the last
// value from the last iteration in the
// for loop in the parallel region
```

parallel_regions/
09_clauses__lastprivate.c

The clause **`lastprivate()`** pertains *only* to the **`for`** construct.
When used, every variable listed is private in the same sense than before, and its value is *not* initialized.

What is affected is the value that the original variable, the one that is declared in the master thread's stack, has *after* the parallel region. It will have the value that the private copy of it has in the last iteration of the for loop.

we'll see in detail how the for loop works and how the work is distributed within it

Managing the shared/private memory

```c
int    myN;
double *array;
#pragma omp threadprivate(myN, array)

#pragma omp parallel
{
   // array does exist and it's private
   // to each thread
   array = ... allocate memory...;
}
// .. something serial here..
#pragma omp parallel
{
   // array does exist here and
   // the allocated memory is available
}
```

parallel_regions/
09_clauses__threadprivate.c

The clause **`threadprivate`** applies to global variables and has a global scope.
`threadprivate` variables are private variables that do exist all along the lifetime of the process.
I.e. they are private variables that do not die in between of two different parallel regions.

note: when using `threadprivate`, the dynamic thread creation is not allowed, i.e. the number of threads in each parallel region is constant.

Managing the shared/private memory

```c
int golden_values[3];
#pragma omp threadprivate(golden_values)

for( int i = 0; i < N; i++ )
{
    get_golden_values();
   #pragma omp parallel copyin(golden_values)
    {
      // each thread uses golden_values[]
    }
}
```

The clause **`copyin()`** applies to parallel and worksharing (e.g. `for`) constructs.
This clause basically provides a way to perform a **broadcast of `threadprivate` variables** from the master thread (i.e. the thread 0) to the corresponding `threadprivate` variables of other threads.

The copying happens at the creation of the region, before the associated structured block is executed.

parallel_regions/
09_clauses__copyin.c, 09_clauses__copyin__clarify.c

Managing the shared/private memory

```
#pragma omp parallel
 {
    double seed[2];

   #pragma omp single copyprivate(seed)
    {
      // something happens here and the
      // thread that executes this block
      // initializes the seed[2] array
    }

  // at this point the values of the seed[2]
  // array have been propagated to all the
  // other threads
}
```

parallel_regions/
09_clauses__copyprivate.c

The clause **`copyprivate()`** applies only to **`single`** construct.

This clause provides a mechanism to propagate the values of private variables, including threadprivate, from a thread to the others inside a parallel region.
The copying is ultimated before any threads leave the implicit barrier at then end of the construct.

The OpenMP environmental variables

You can configure the OpenMP behaviour through Internal Control Variables (ICV).
Those are "*conceptual*" variables, meaning that you, as a programmer, are not interested in where and how those internal variables are implemented; you are only interested in how to access and use them.
These variables have different scopes:

- *Global scope* applies to the whole program, it is fixed once at the begin (there's only one, to my knowledge)
- *Device scope* OpenMP, since v4.0, can deploy threads on heterogeneous platforms (CPUs, GPUs, co-processors, …); some ICV are naturally different on different devices
- *Task scope* most ICVs have a *local* scope, i.e. each OMP task(*) holds its own values and can change them; when new tasks are created with either a `parallel` or `task` directives, they inherit the ICVs. If a task modifies the ICVs, this has effect only during its lifetime and can not be backward-propagated.

(*)a "task" is in general a target to be executed by a thread: for instance, a section of a for loop scheduled for a thread is, in this sense, a "task.

The OpenMP environmental variables

ICV	Scope	Env. Variable	Accessibility from src	
nthreads	TASK	OMP_NUM_THREADS	get / set	Affect **parallel region**
nested	TASK	OMP_NESTED	get / set	
max-active-levels	TASK	OMP_MAX_ACTIVE_LEVELS	get / set	
active-level	TASK	-	get	
dynamic	TASK	OMP_DYNAMIC	get / set	
stacksize	DEVICE	OMP_STACKSIZE	-	Affect **program** execution
threads-limit	TASK	OMP_THREAD_LIMIT	get	
waiting-policy	DEVICE	OMP_WAIT_POLICY	-	
binding	TASK	OMP_PROC_BIND	set	
placement	TASK	OMP_PLACES	-	
cancellation	GLOBAL	OMP_CANCELLATION	get	
default-device	TASK	OMP_DEFAULT_DEVICE	get / set	
run-schedule	DEVICE	OMP_SCHEDULE	get / set	Affect **auto-parallelization** of loops
default-schedule	DEVICE	-	-	

Lab exercise / 1

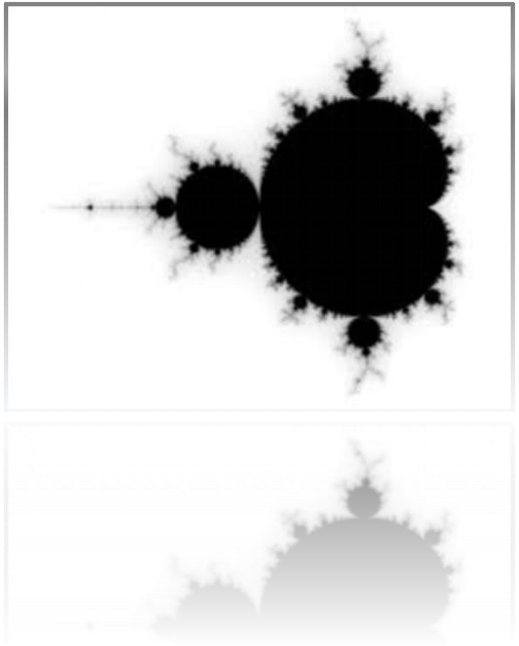
I propose you to write a code here and now, in the next 20 minutes, using what you know on OpenMP up to know and drawing from the codes that you find in the examples that we have discussed.

Please, ask about any doubt you may have; let's make this an interactive lab.

`PARALLEL_PROGRAMMING/OPENMP/exercises/`
`lab_exercise.c, lab_exercise.v2.c`

let's check together the code that is your starting point

Lab exercise / 2



Let's aim to a more ambitious and, likely, funny, exercise.
Write a code that calculates the Mandelbrot set that, as you may know, is a gorgeous fractal generated by the very simple equation

$$f_c(z) = z^2 + c$$

in the complex plane.

You find the details in
`/PARALLEL_PROGRAMMING/OpenMP/exercises/exercises.pdf`

that’s all, have fun