OpenMP Tutorial

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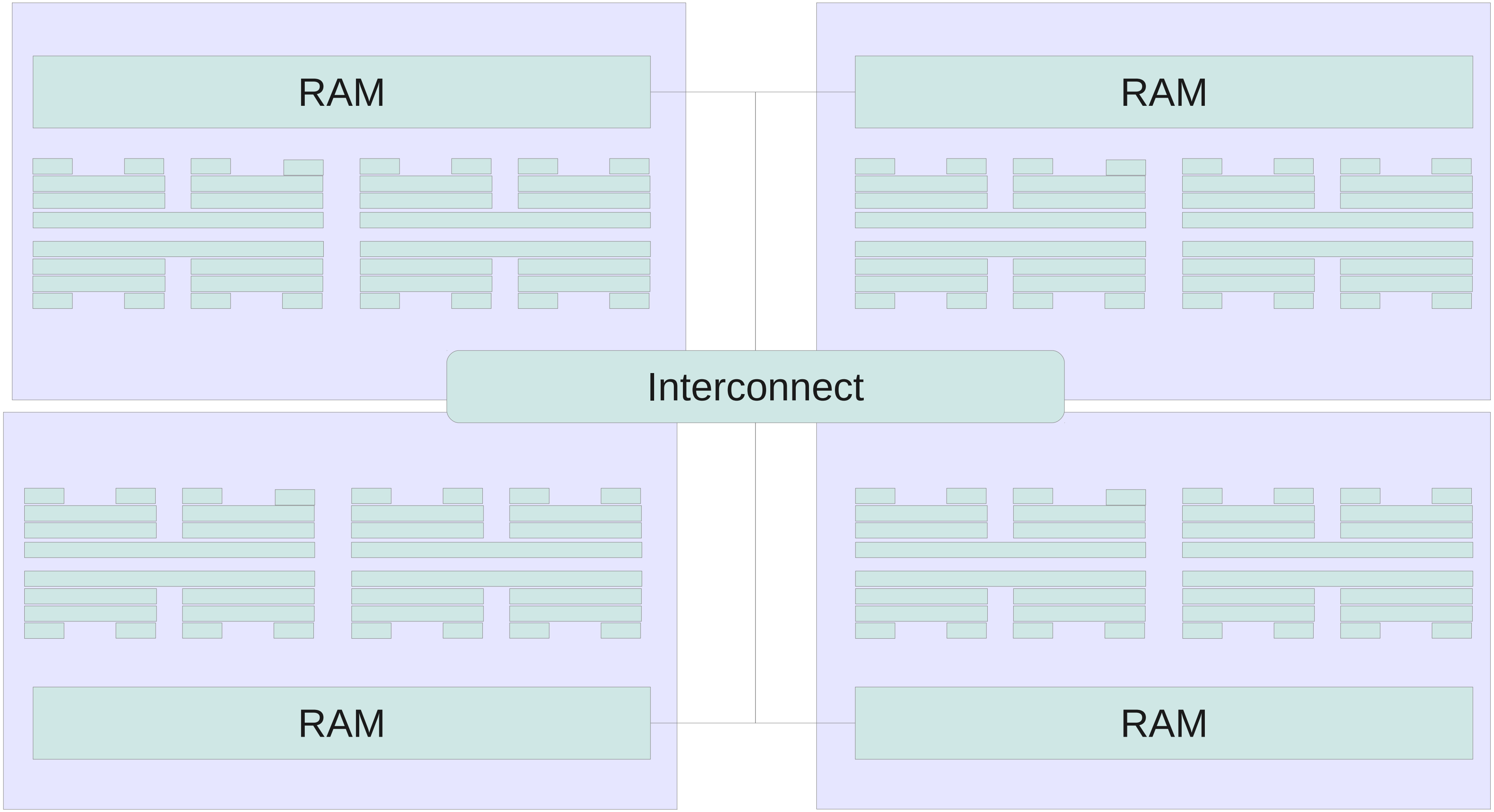
Parallel Architectures

Parallel Architectures

- NUMA (Non-Uniform Memory Access) architecture.
- Linking several SMPs.
- Coherency not maintained.

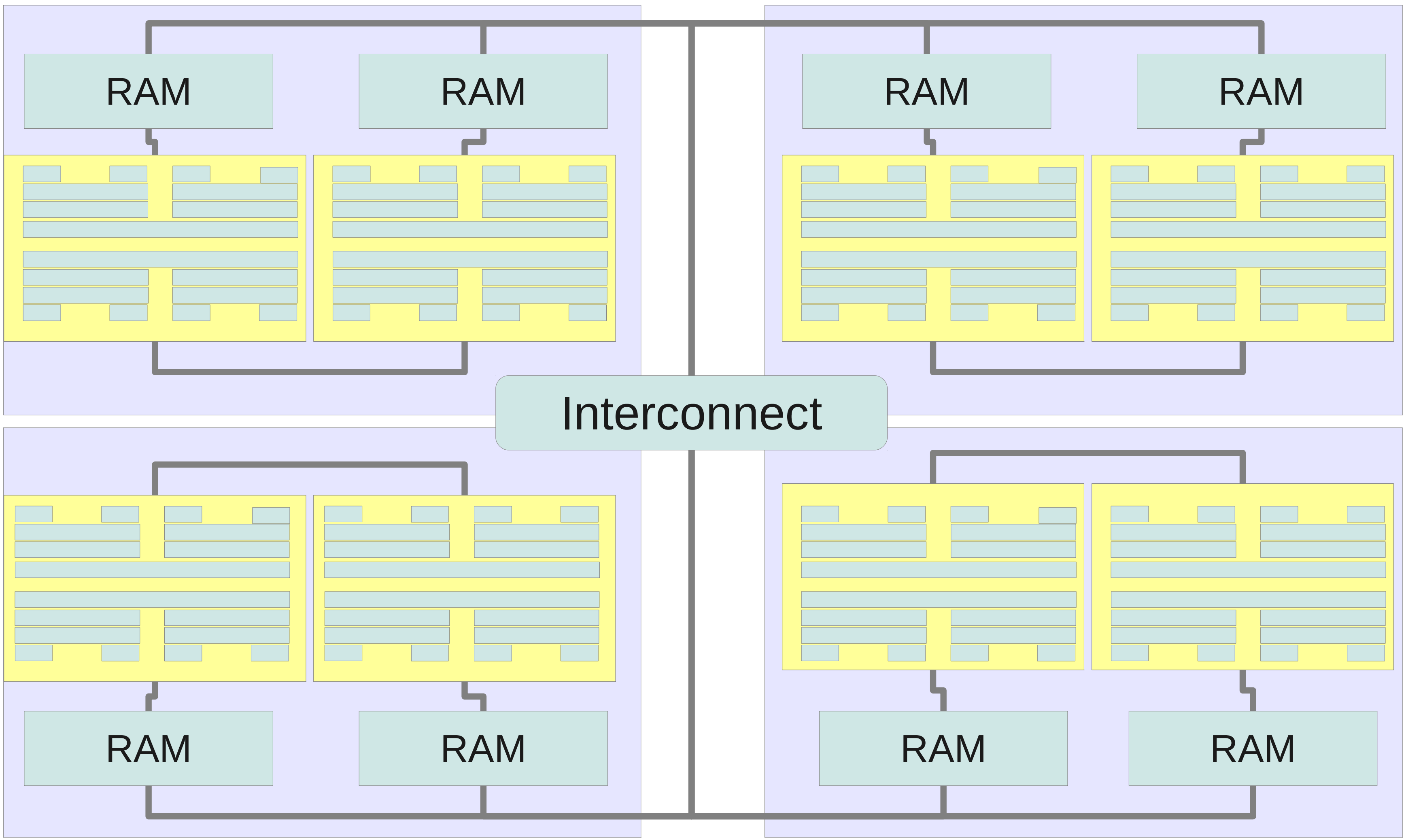
Distributed Memory



Parallel Architectures

- ccNUMA (*cache coherent Non-Uniform Memory Access*) architecture.
- Communication between cache controllers to maintain coherency.
- Consistent memory image.

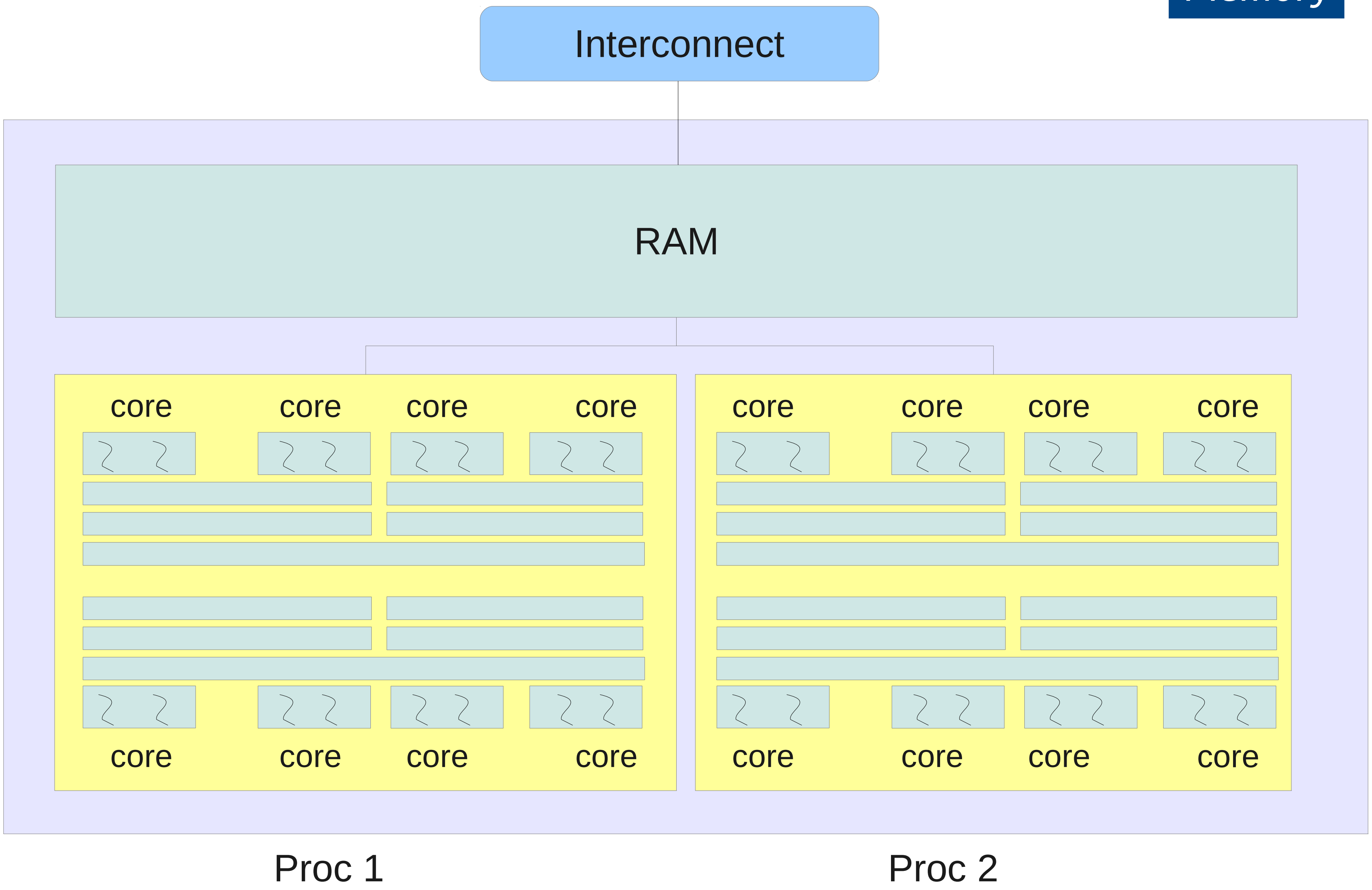
Distributed Memory



Parallel Architectures

- NUMA node - SMP architecture.

Shared Memory



Programing Models

Programing Models

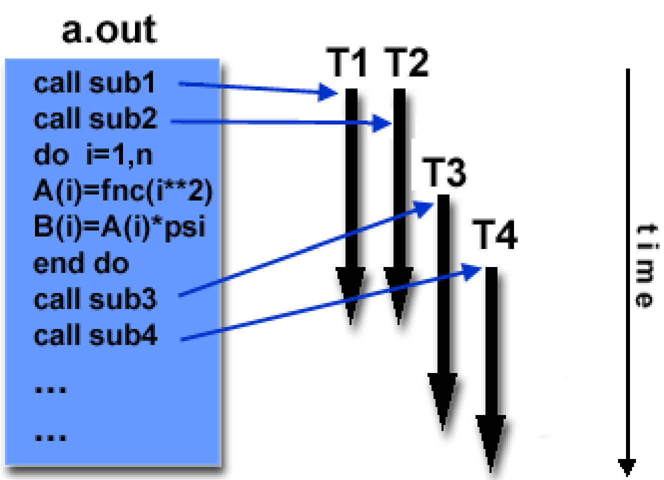
Distributed Memory
MPI

- Message Passing Interface (*ie. MPI*).
- Explicit model – message sending/receiving for:
  - ✓ Data exchange.
  - ✓ Synchronization.
  - ✓ Communication.
- Programmer should express the parallelism explicitly.
- MPI subroutines used at source level.
- The "*de facto*" industry standard for message passing.

Programing Models

Shared Memory
Threads

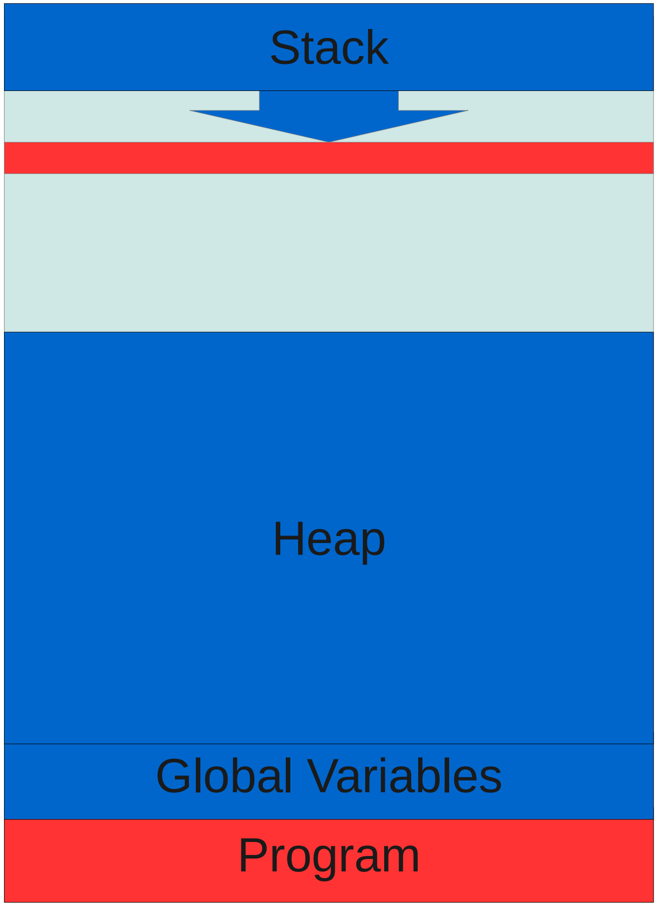
- Thread model
  - One program with multiple subroutines.
  - One cook book and multiple cookers reading different pages.
  - Each thread Ti has local data.
  - Each thread accesses to the global memory → potential synchronization.



Programing Models

Shared Memory
Threads

- What is a thread?
  - ✓ Smallest unit scheduled by the OS.
  - ✓ Different threads belong to one process.
  - ✓ Thread = lightweight process.
- One thread owns:
  - ✓ A stack.
  - ✓ A set of registers (ie. a context).

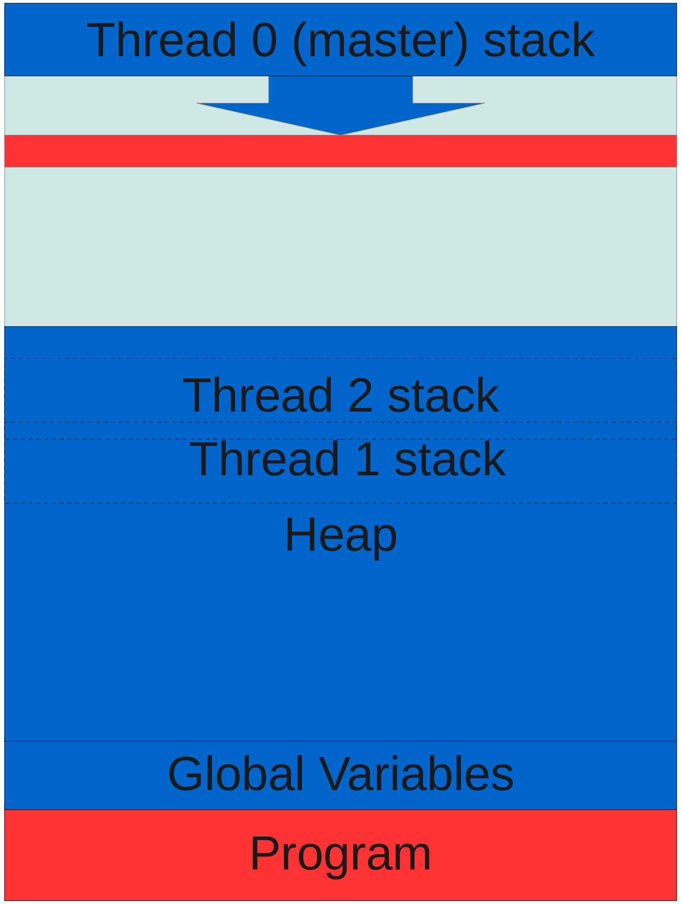


Memory
-
Sequential Process

Programing Models

Shared Memory Threads

- Multiple threads share the same @ space.
- The threads stacks are located in the heap.
- The thread's stack has a fixed size.
- Only the master thread's stack size increases.
- Global variables are shared between threads.
- Communication between threads via the memory.



Memory
-
Multi-threaded Process

Programing Models

Shared Memory
Threads → OpenMP

- Two APIs for kernel threads manipulation:
  - POSIX threads: linux, FreeBSD, MacOS, Solaris, ...
  - Windows threads

- Different programing models for shared memory:
  - *OpenMP*, CILK, TBB, CnC, Chapel

- Focus on the *OpenMP* programing model

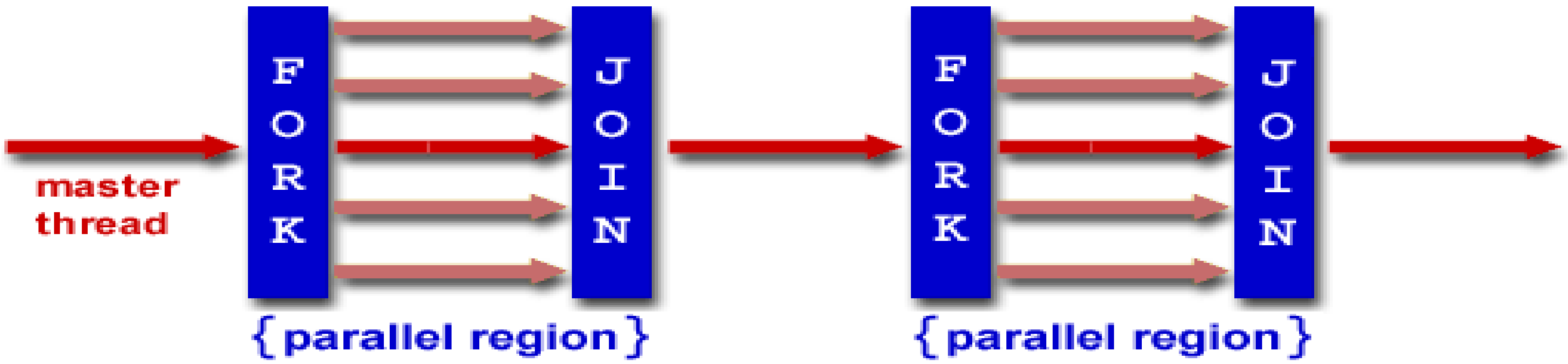
- *OpenMP 3.1* specifications
  http://www.openmp.org/mp-documents/OpenMP3.1.pdf

OpenMP

OpenMP

- OpenMP (Open Multi-Processing) is a C/C++ and Fortran Application Programming Interface for shared memory architectures.

- OpenMP is based on the Fork and Join model:

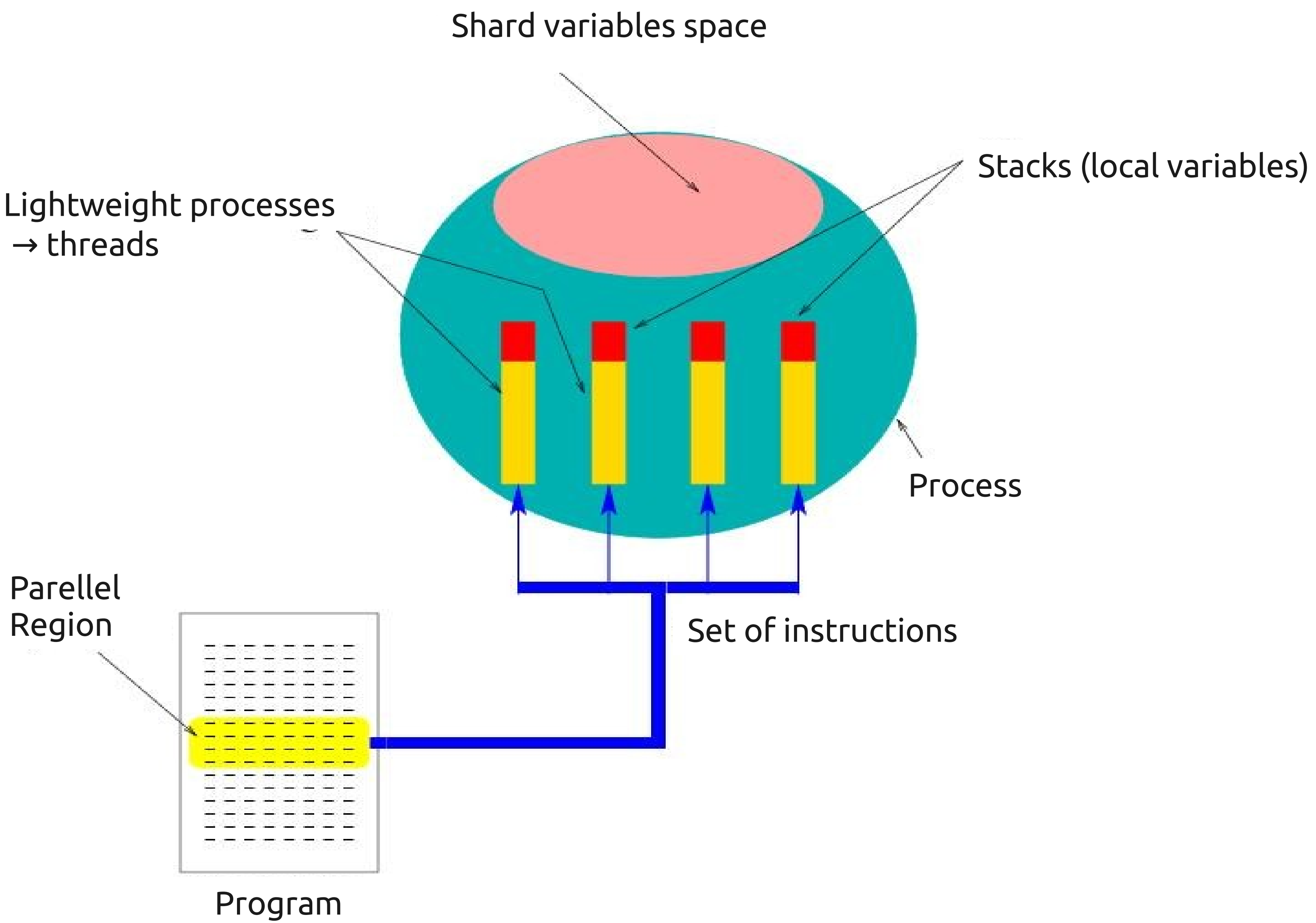


- OpenMP consists in:
  - ✓ A set of compiler directives.
  - ✓ Library functions calls
  - ✓ Environment variables

OpenMP

- An OpenMP program is executed by one process → thread master.
- The process activates several lightweight processes (ie. threads) when a parallel region starts → Fork.
- The code of the parallel region is duplicated and each thread executes that code.
- Different threads executes the code at the same time.
- At the end of a parallel region (ie. join), only the master thread continues execution.
- During the execution a the threads, a variable can be read/written:
  - ✓ If the variable is in the thread's stack → private variable
  - ✓ If the variable defined in a shared memory space → shared variable

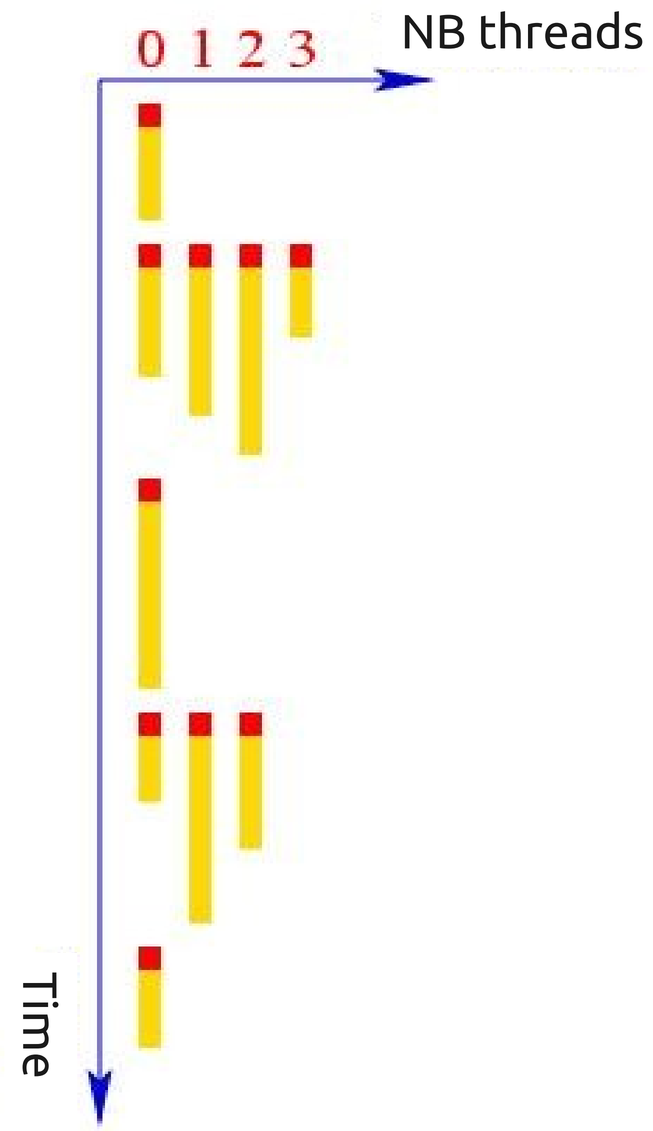
OpenMP



Shard variables space
Stacks (local variables)
Lightweight processes
→ threads
Process
Parellel
Region
Set of instructions
Program

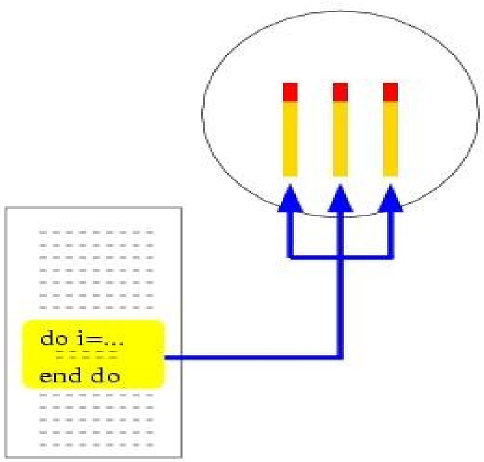
OpenMP

- An OpenMP program alternates sequential and parallel regions.
- The sequential region is always executed by the thread master → thread 0.
- A parallel region is executed by different threads at the same time.
- The threads may share the work inside the parallel region.

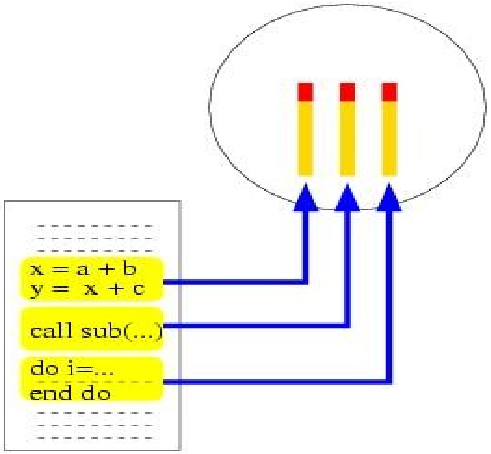


OpenMP

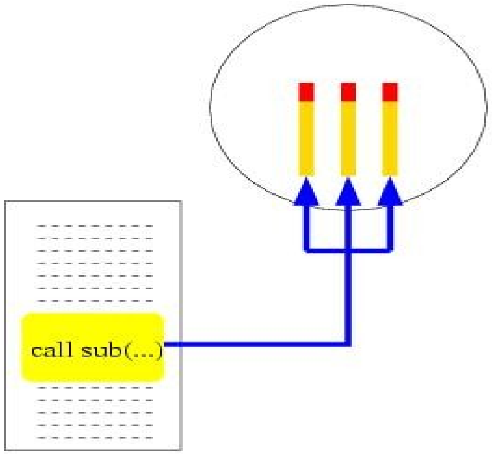
- What is the work sharing between threads?
  - Share the iteration space of a loop between threads.
  - Execute different sections of a program but one section per thread.
  - Execute different occurrences of a procedure by different threads.



Loop Level Parallelism



Parallel Sections

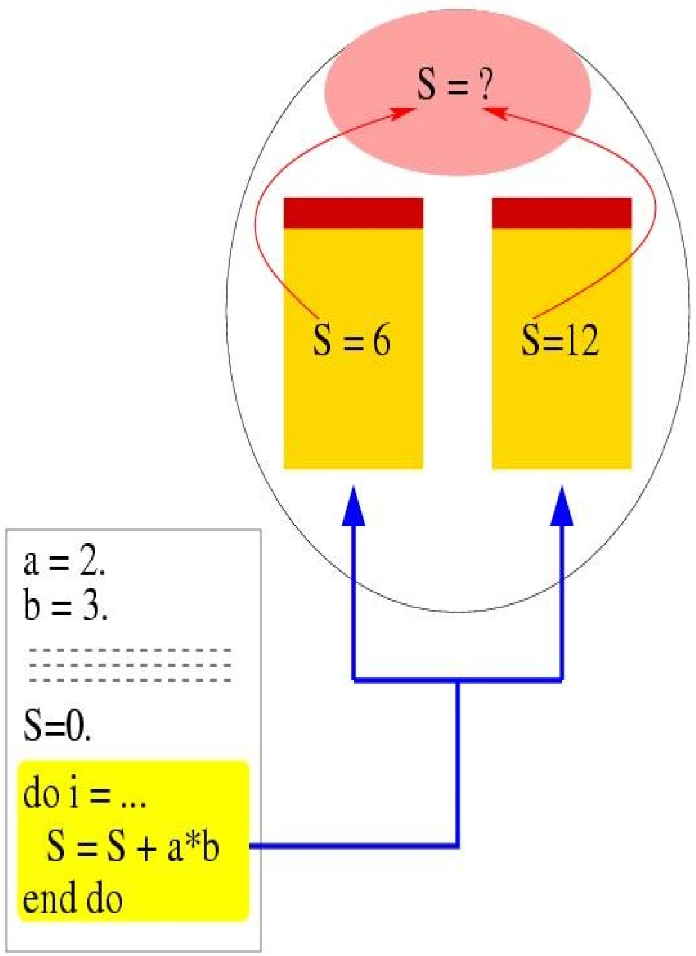


Parallel Procedures

- What is data race?
  - It is the access to a shared variable by different threads and at least one access is a write.

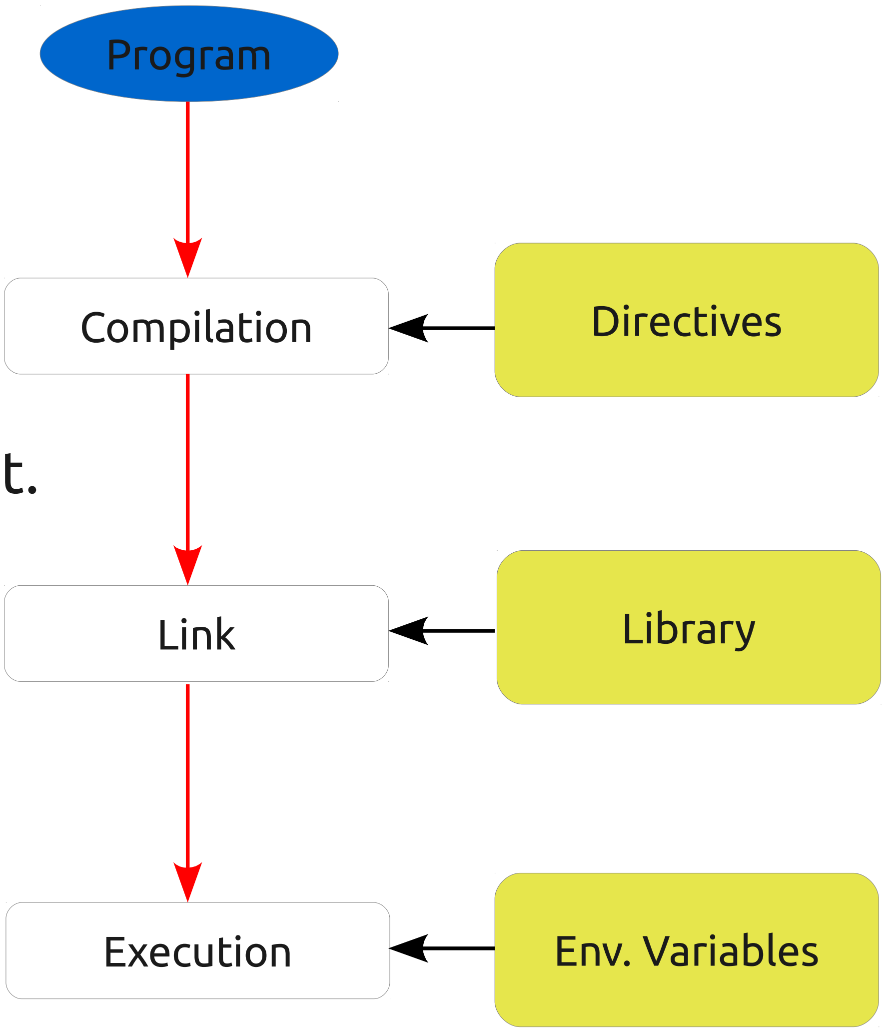
- In case of data race, synchronization between threads is mandatory.

- For example, in case of a reduction, a synchronization is needed to avoid the modification, of the value of the shared variable, in an incorrect order.



OpenMP

- Compilation directives:
  - Define the work sharing.
  - Synchronization.
  - Privacy of variables.
  - If correct flag not set, the compiler consider the directive as a comment.
- Library functions calls:
  - It is loaded at link.
- Environment variables:
  - When set up, their values are considered at execution time.



OpenMP - Syntax

- The OpenMP directives are:
  - Inserted in the source code by the programmer
    OR
  - Inserted automatically in the source code (ie. automatic parallelization)

- An OpenMP directive has the following shape:

  #pragma omp *directive [clause[clause]...]* *for C/C++*

  sentinel directive [clause[clause]...] *for Fortran*

- There is an include file “*omp.h*”*:*
  - It defines all OpenMP functions.
  - It should be included in each OpenMP program to be able to use the functions.

OpenMP - Syntax

```
#include <omp.h>

...

#pragma omp parallel private(a,b) \
                shared(d,c)
{

...

}
```

OpenMP – Parallel Region

OpenMP
Parallel Region Construction

- In a parallel region by default the variables are shared.
- In a parallel region all threads execute the same code.
- At the end of the parallel region there is an implicit barrier for synchronization.
- No branches inside or outside a parallel region, neither in any other OpenMP construct.

OpenMP
Parallel Region Construction

```
#include <stdio.h>
#include <omp.h>

int main(void)
{
   int a;        int   p;
   a = 10000;   p = 0;
   #pragma omp parallel
   {
#ifdef _OPENMP
      p=omp_in_parallel();
#endif
      printf("a = %d ; p = %d\n",a,p);
   }
   return 0;
}
```

OpenMP
Parallel Region Construction

```
> gcc … -fopenmp -o omp omp.c
> export OMP_NUM_THREADS=8
> ./omp

a = 10000 ; p = 1
a = 10000 ; p = 1
a = 10000 ; p = 1
a = 10000 ; p = 1
a = 10000 ; p = 1
a = 10000 ; p = 1
a = 10000 ; p = 1
a = 10000 ; p = 1
```

OpenMP
Parallel Region Construction

- It is possible to change the default status of variables in the parallel region construct. This can be done using the clause ***DEFAULT*** .

- If a variable has a ***PRIVATE*** status, it is located in the thread's stack. Its value is undefined at the entry of a parallel region.

OpenMP
Parallel Region Construction

```
#include <stdio.h>
#include <omp.h>

int main(void)
{
   int a = 10000;
   int p = 0;
   #pragma omp parallel private(a)
   {
#ifdef _OPENMP
      p=omp_in_parallel();
#endif
      printf("a = %d ; p = %d\n",a,p);
   }
   return 0;
}
```

OpenMP
Parallel Region Construction

```
> gcc … -fopenmp -o omp omp.c
> export OMP_NUM_THREADS=8
> ./omp

a = 0 ; p = 1
a = 0 ; p = 1
a = 0 ; p = 1
a = 0 ; p = 1
a = 32621 ; p = 1
a = 0 ; p = 1
a = 0 ; p = 1
a = 0 ; p = 1
```

OpenMP
Parallel Region Construction

- The clause ***FIRSPRIVATE*** forces the initialization of the private varibale to the last value it has right before the parallel region.

OpenMP
Parallel Region Construction

```
#include <stdio.h>
#include <omp.h>

int main(void)
{
   int a;
   a = 50000;

   #pragma omp parallel firstprivate(a)
   {
        a += 1111;
     printf("a = %d\n",a);
   }

   printf*("After parallel region, a = %d\n",a);

   return 0;
}
```

OpenMP
Parallel Region Construction

```
> gcc … -fopenmp -o omp omp.c
> export OMP_NUM_THREADS=8
> ./omp

a = 51111
a = 51111
a = 51111
a = 51111
a = 51111
a = 51111
a = 51111
a = 51111
After parallel region, a = 50000
```

OpenMP
Scope of a Parallel Region

- The influence of a parallel region goes beyond the region's “lexical” scope. It is extended to the code of the subroutines called in the parallel region.

- This is called ***the dynamic scope.***

OpenMP
Scope of a Parallel Region

```
int main(void)
{
   void sub(void);

   #pragma omp parallel
   {
      sub();
   }
   return 0;
}
```

```
#include <stdio.h>
#include <omp.h>

void sub(void)
{
   int p=0;

#ifdef _OPENMP
   p = omp_in_parallel();
#endif

   printf("Parallel? :
     %d\n", p) ;
}
```

OpenMP
Scope of a Parallel Region

```
> gcc …  -fopenmp -o omp omp.c sub.c
> export OMP_NUM_THREADS=8
> ./omp

Parallel? : 1
Parallel? : 1
Parallel? : 1
Parallel? : 1
Parallel? : 1
Parallel? : 1
Parallel? : 1
Parallel? : 1
```

OpenMP
Scope of a Parallel Region

- In a subroutine called in a parallel region, the local variables are implicitly private to each thread and defined in its corresponding stack.

```c
int main(void)
{
   void sub(void);

   #pragma omp parallel \
          default(shared)
   {
      sub();
   }
   return 0;
}
```

```c
#include <stdio.h>
#include <omp.h>

void sub(void)
{
    int a;
    a = 50000;

    a = a + omp_get_thread_num();
    printf("a = %d\n", a);
}
```

OpenMP
Scope of a Parallel Region

```
> gcc …  -fopenmp -o omp omp.c sub.c
> export OMP_NUM_THREADS=8
> ./omp

a = 50000
a = 50001
a = 50007
a = 50005
a = 50004
a = 50003
a = 50002
a = 50006
```

OpenMP – Work Sharing

OpenMP
Work Sharing

- Using OpenMP functions to create a parallel region is enough.

- The programmer has to explicitly divide the work, the data and make sure not to have any data race.

- OpenMP has directives that take care of that in a good way:
  - ✓ FOR directive
  - ✓ SECTIONS directive
  - ✓ WORKSHARE directive

OpenMP
Work Sharing – FOR directive

- A ***for*** directive is used inside a parallel region.

- Different clauses can be used with the **for** directive:
  - ✓ ***private*** – makes the variable private
  - ✓ ***firstprivate*** – makes the variable private and assign it the last value it has right before the ***for*** region
  - ✓ ***lastprivate*** – makes the variable private and keep the value it has at the last iteration of the loop, outside the ***for*** region
  - ✓ ***reduction*** – a private copy for each variable listed is created for each thread. The reduction variable is applied to all private copies of the shared variable. The final result is written to the global shared variable.

OpenMP
Work Sharing – FOR directive

```
#define length 500

int main(void)
{
    int A[length];
    int B[length];
    int dot = 0;

     Init(A,B);

    #pragma omp parallel default(none) shared(A,B,dot)
    {
                int k;

                #pragma omp for reduction(+:dot)
                for (k=0 ; k<length ; ++k){
                  dot += A[k] * B[k];
                }

             }

    return 0;
}
```

OpenMP
Work Sharing – FOR directive

- Different scheduling can be applied to the threads:
  - ✓ Static
  - ✓ Dynamic
  - ✓ Guided

- The clause ***SCHEDULE*** allows to choose the scheduling:

  #pragma omp ***for schedule(static|dynamic|guided)***

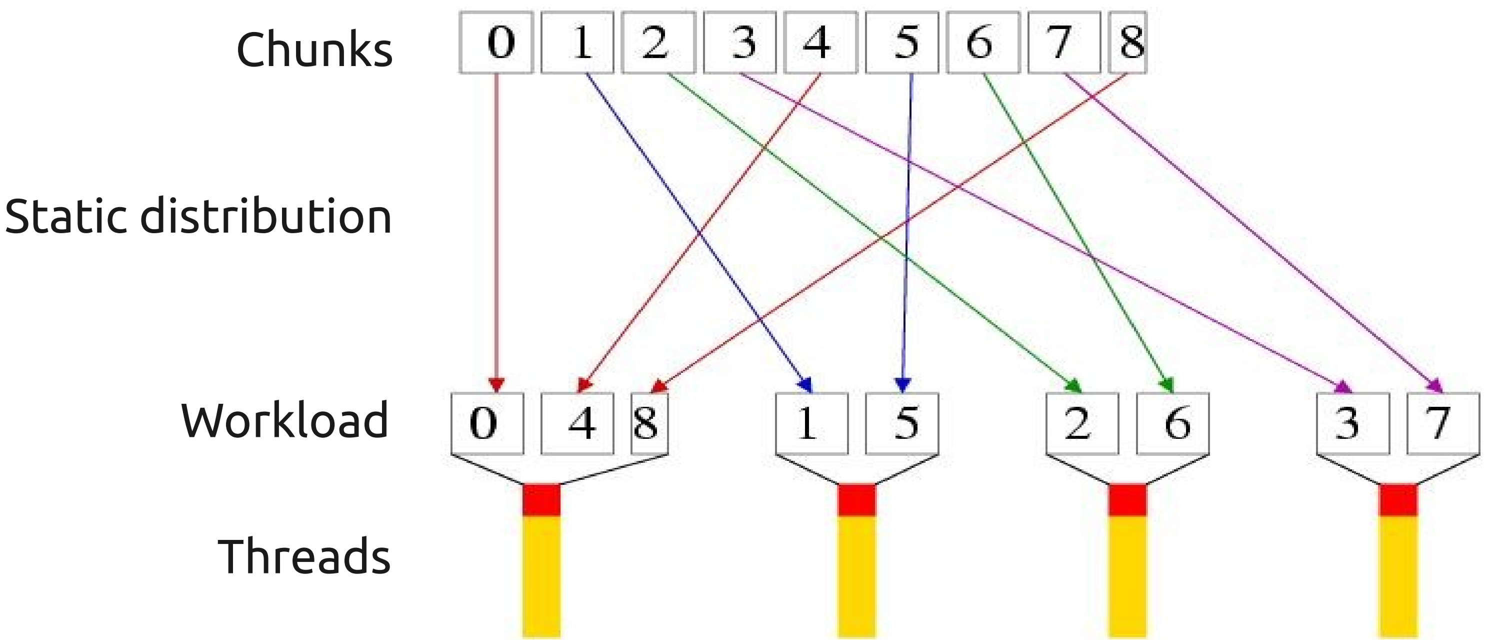
- Choosing a right scheduling for a loop is a major criterion for a good load balancing.

- There is an implicit barrier at the end of a ***for*** construct unless a ***NOWAIT*** clause is specified.

OpenMP
Work Sharing – FOR directive – SCHEDULE clause

- ***Schedule(static,** chunk_size)* – Iterations are divided into chunks of *chunk_size*. The chunks are assigned to the threads of the team in a round-robin way in the order of the thread number.

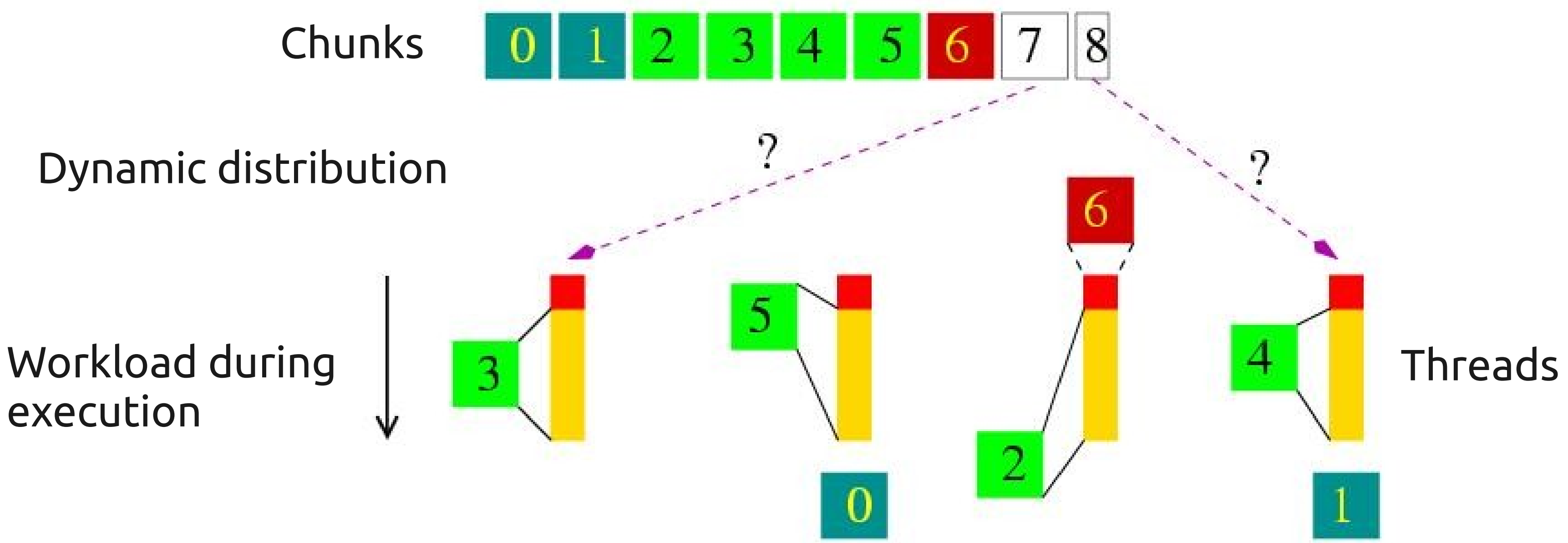
- If no *chunk_size* is specified the iteration space is divided into chunks that have almost the same size. At most only one chunk is assigned to one thread.



OpenMP
Work Sharing – FOR directive – SCHEDULE clause

- ***Schedule(dynamic,*** *chunk_size)* – Iterations are distributed to the threads in chunks, of *chunk_size*, when the threads request them. Each thread executes a chunk, and it finishes, it requests another chunk until no more chunks to be distributed.

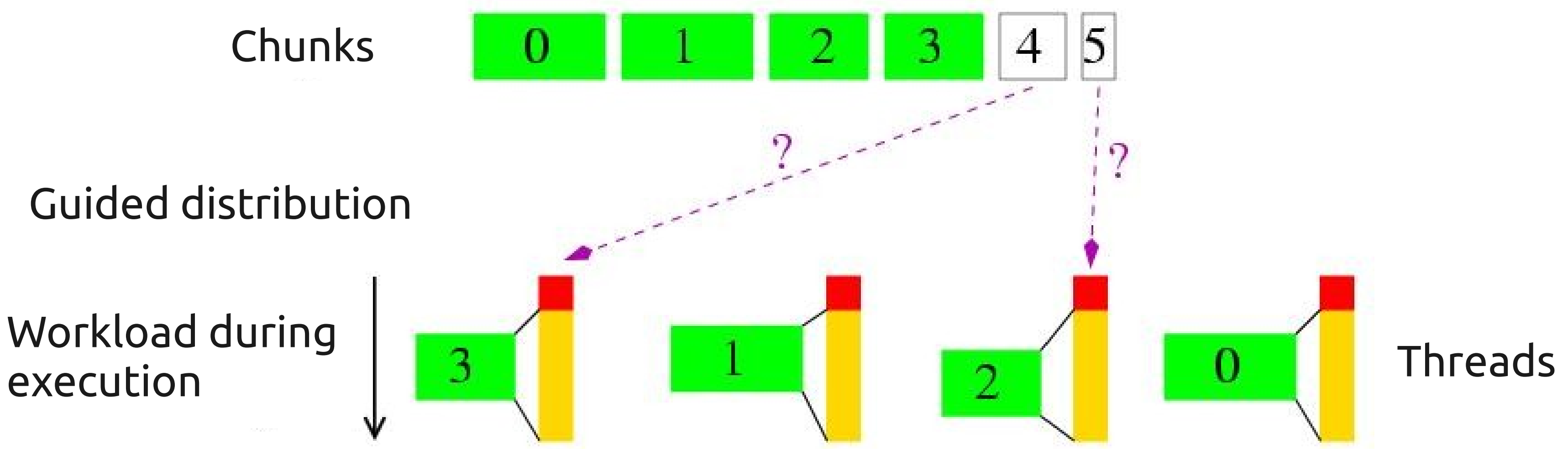
- If no *chunk_size* is specified the default is 1.



OpenMP
Work Sharing – FOR directive – SCHEDULE clause

- ***Schedule(guided,** chunk_size**)*** – Iterations are assigned to the threads in chunks when the threads request them. The size of each chunk is proportional to the number of unassigned iterations divided by the number of threads decreasing to *chunk_size*.

- If no *chunk_size* is specified the default is 1.



OpenMP – Exclusive Execution

OpenMP
Exclusive Execution

- In case the programmer wants to execute a task by only one thread and keep the other threads away from this task, two directives can be used:
  - ✓ SINGLE
  - ✓ MASTER

OpenMP
Exclusive Execution – SINGLE directive

- The ***SINGLE*** construct specifies that the associated structured block is executed by only one of the threads in the team (not necessarily the master thread).

- It is in general the first thread arriving to the ***SINGLE*** construct

- The other threads that do not execute the block wait at an implicit barrier at the end of the single construct unless a ***NOWAIT*** clause is specified.

- The different clauses that can be used in a ***SINGLE*** construct are:
  - ✓ Private
  - ✓ Firstprivate
  - ✓ Copyprivate

- The ***COPYPRIVATE*** clause uses a private variable to broadcast a value from one thread to the other threads of the team.

OpenMP
Exclusive Execution – SINGLE directive

```
#include <stdio.h>
#include <omp.h>

int main(void)
{
  int rank;
  int a;

  #pragma omp parallel private(a,rank)
  {
    a = 50000;

   #pragma omp single
    {
        a = -50000;
    }

    rank=omp_get_thread_num();
    printf("Rank : %d ; A = %d\n",
                 rank,a);
  }
  return 0;
}
```

```
> gcc …  -fopenmp -o omp omp.c
> export OMP_NUM_THREADS=8
> ./omp

 Rank : 6 ; A = 50000
 Rank : 0 ; A = 50000
 Rank : 3 ; A = 50000
 Rank : 4 ; A = 50000
 Rank : 1 ; A = 50000
 Rank : 5 ; A = 50000
 Rank : 7 ; A = -50000
 Rank : 2 ; A = 50000
```

OpenMP
Exclusive Execution – SINGLE directive

```
#include <stdio.h>
#include <omp.h>

int main(void)
{
  int rank;
  int a;

  #pragma omp parallel private(a,rank)
  {
      a = 50000;

      #pragma omp single copyprivate(a)
      {
          a = -50000;
      }

      rank=omp_get_thread_num();
      printf("Rank : %d ; A = %d\n",rank,a);
  }
  return 0;
}
```

```
> gcc …  -fopenmp -o omp omp.c
> export OMP_NUM_THREADS=8
> ./omp

 Rank : 6 ; A = -50000
 Rank : 0 ; A = -50000
 Rank : 3 ; A = -50000
 Rank : 4 ; A = -50000
 Rank : 1 ; A = -50000
 Rank : 5 ; A = -50000
 Rank : 7 ; A = -50000
 Rank : 2 ; A = -50000
```

OpenMP - Synchronization

OpenMP
Synchronization

- Synchronization is important:
  - ✓ To check that all threads executed the same number of instructions in the program.
  - ✓ To order the execution of different threads that are executing the same portion of code and impacting one or multiple shared variables that must be a coherent value in the memory.
  - ✓ To synchronize some threads (at least two) from the same team (lock).

OpenMP
Synchronization – Explicit BARRIER

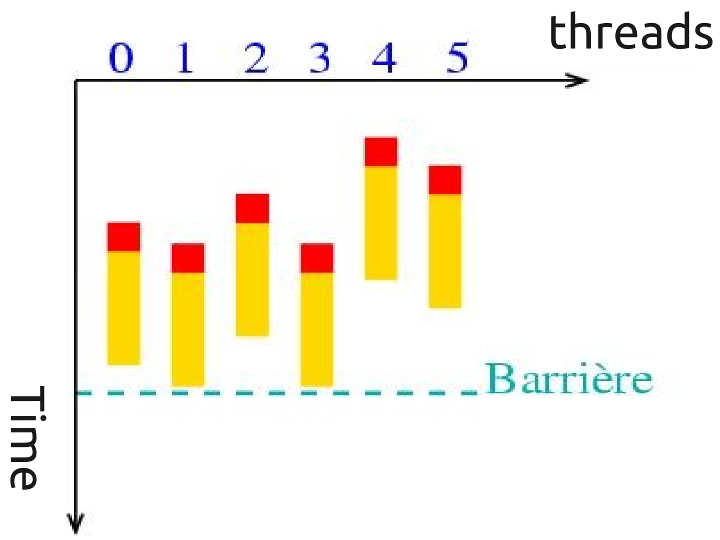
- There is an implicit barrier at the end of each ***PARALLEL*** construct at the end each ***FOR*** construct.

✓ This barrier can be bypassed if the clause ***NOWAIT*** is used.

- An explicit barrier can be forced for synchronization using the ***BARRIER*** directive.

- The ***BARRIER*** directive synchronizes all threads of the same team in a parallel region.

- Each thread waiting at a barrier do not continue the execution of the program until all threads reach the same barrier.



OpenMP
Synchronization – Explicit BARRIER

```
#pragma omp parallel private(TID)
{
    double start,stop;

    TID=omp_get_thread_num();

    start = omp_get_wtime();

    if (TID < omp_get_num_threads()/2)
        sleep(3);

    stop = omp_get_wtime();

    printf("%.0f seconds elapsed before barrier, thread %d\n",
                 stop-start,TID);

    #pragma omp barrier

    stop = omp_get_wtime();

    printf("%.0f seconds elapsed after barrier, thread %d\n", stop-
                 start,TID);
}
```

OpenMP
Synchronization – Explicit BARRIER

```
> gcc …  -fopenmp -o omp omp.c
> export OMP_NUM_THREADS=8
> ./omp

 0 seconds elapsed before barrier, thread 7
 0 seconds elapsed before barrier, thread 5
 0 seconds elapsed before barrier, thread 4
 0 seconds elapsed before barrier, thread 6
 3 seconds elapsed before barrier, thread 0
 3 seconds elapsed before barrier, thread 3
 3 seconds elapsed before barrier, thread 1
 3 seconds elapsed before barrier, thread 2
 3 seconds elapsed after barrier, thread 1
 3 seconds elapsed after barrier, thread 0
 3 seconds elapsed after barrier, thread 7
 3 seconds elapsed after barrier, thread 2
 3 seconds elapsed after barrier, thread 4
 3 seconds elapsed after barrier, thread 3
 3 seconds elapsed after barrier, thread 6
 3 seconds elapsed after barrier, thread 5
```

OpenMP
Synchronization – ATOMIC directive

- An ***ATOMIC*** directive ensures that a specific shared storage location is updated in memory by one thread at a time.

- Simultaneous read and writing in the same statement may result in a indeterminate value.

- The ***ATOMIC*** directive is applied on the instruction that immediately follows the construct.

OpenMP
Synchronization – ATOMIC directive

```
#include <stdio.h>
#include <omp.h>

int main(void)
{
  int counter, rank;

  counter = 50000;

  #pragma omp parallel default()none \
          private(rank) shared(counter)
  {
    rank=omp_get_thread_num();

    #pragma omp atomic
    counter++;

    printf("Rank : %d ; counter = %d\n",
                  rank,counter);
  }

  printf("In total, counter = %d\n",counter);
  return 0;
}
```

```
> gcc …  -fopenmp -o omp omp.c
> export OMP_NUM_THREADS=8
> ./omp

 Rank : 0 ; counter = 50002
 Rank : 7 ; counter = 50001
 Rank : 1 ; counter = 50003
 Rank : 3 ; counter = 50004
 Rank : 4 ; counter = 50005
 Rank : 2 ; counter = 50006
 Rank : 6 ; counter = 50007
 Rank : 5 ; counter = 50008
 In total, counter = 50008
```

OpenMP
Synchronization – CRITICAL directive

- A ***CRITICAL*** directive ensures that a specific region in the program is executed by one thread at a time.
- A ***CRITICAL*** directive can be considered as a general version of the ***ATOMIC*** directive.
- For better performance it is not recommended to use a ***CRITICAL*** directive to do an ***ATOMIC*** operation.

OpenMP
Synchronization – CRITICAL directive

```
#include <stdio.h>

int main(void)
{
    int s, p;

    s = 0, p = 1;

    #pragma omp parallel
    {
        #pragma omp critical
        {
            s++;
            p*=2;
        }
    }
    printf("Total sum and product: %d, %d\n",s,p);

    return 0;
}
```

OpenMP – Nested Parallelism

OpenMP
Nested Parallelism

- The OpenMP standard allows nested parallelism.
- This nesting consists in having a parallel region inside another parallel region.
- ATTENTION! The threads IDs are *local* to each parallel region. Different threads with the same IDs may exist!
- **Pros** – Exploit the parallelization at different levels.
- **Cons** – Overhead of the parallel region creation/destruction.

OpenMP
Nested Parallelism

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

  #pragma omp parallel
  {
    work(...);
  }
}
```

```
void work(...) {
  /* declarations */
  #pragma omp for
  for (j=0; j<m; ++j)
  {
   ...
  }
}
```

OpenMP – API + Env. Variables

OpenMP
Programing Interface

- ***omp_set_num_threads()***
  - ✓ Defines the number of threads in a parallel region (unless a *num_threads* clause is specified).

- ***omp_get_num_threads()***
  - ✓ Returns the number of threads available in the current parallel region.

- ***omp_get_thread_num()***
  - ✓ Returns the ID of the current thread in the current team.

- ***omp_get_max_threads()***
  - ✓ Returns the maximum number of threads that can be created in one parallel region (unless the *num_thread* clause is specified).

OpenMP
Programing Interface

- ***omp_get_num_procs()***
  - ✓ Returns the number of available logical processors.
- ***omp_in_parallel()***
  - ✓ Indicates if we are in a parallel region or not.
- ***omp_set_nested()***
  - ✓ Activates parallel region nesting
- ***omp_get_nested()***
  - Indicates if the nesting is allowed or not.

OpenMP
Environment Variables

- ***OMP_NUM_THREADS***
  - Maximum number of threads for a parallel region
- ***OMP_SCHEDULE*** = *static|dymanic|guided [chunk_size]*
  - Strategy chosen when the ***schedule(runtime)*** clause is specified in the code.
- ***OMP_NESTED***
  - Indicates to the OpenMP runtime if the nesting parallelism is allowed.

What Should Be Done To Avoid Mistakes?

OpenMP
Errors to Avoid When Using OpenMP

Default Shared Attributes

- The *implicit* trap:
  - ✓ What is the relation between the variables?
  - ✓ Solution: be explicit on the variable status →

!!!

!!!!! USE DEFAULT(NONE) !!!!!

!!!

Default Shared Attributes

```
int main(int argc, char **argv)
{
   int i, n;
   int h, x, sum;

   n = atoi(argv[1]);
   h = 2;
   sum = 0;

   #pragma omp parallel for reduction(+:sum) shared(h)
    for (i=0 ; i<=n ; i++) {
      x = h * (i + 5);
      sum += (1 + x*x);
    }

   return h * sum;
}
```

OpenMP
Errors to Avoid When Using OpenMP

Private Variables

- Even when using ***default(none)*** the programmer may forget that:
  - ✓ A private variable has an undefined value at the entry of a parallel region.
  - ✓ The value of the original variable is undefined at the exit of the parallel region.

Private Variables

```
int main(int argc, char **argv)
{
    int i,a,b,c,n;

    n=atoi(argv[1]);
    a = b = 0;

    #pragma omp parallel for private(i,a,b)
    for (i=0; i<n; ++i) {
        ++b;
        a = b + i;
    }
    c = a + b;
    return c;
}
```

OpenMP
Errors to Avoid When Using OpenMP

Private Variables

```
int main(int argc, char **argv)
{
    int i,a,b,c,n;

    n=atoi(argv[1]);
    b = 0;

    #pragma omp parallel for firstprivate(b)\
                             lastprivate(a,b)
    for (i=0; i<n; ++i) {
        ++b;
        a = b + i;
    }
    c = a + b;
    return c;
}
```

Bad Use of Master Construct

- The programmer may forget that there is ***no implicit barrier*** at the end of the ***MASTER*** construct.

```
int main(void)
{
    int xInit, xLocal;

    #pragma omp parallel shared(xInit) private(xLocal)
    {
        #pragma omp master
        { xInit = 10; }

        xLocal = xInit;
    }
}
```

OpenMP
Errors to Avoid When Using OpenMP

Summary

- Use ***default(none)***
- Use ***default(none)***
- Use ***default(none)***
- Check the scope of variables in the parallel region.
- Check that the private variables are *protected* when concurrent access.
- Initialize the private variables.
- Use ***default(none)!***

More Slides

OpenMP
Work Sharing – SECTIONS directive

- A section is a portion of code or a block executed by one thread.

- The ***SECTIONS*** directive is a non-iterative construct that contains several blocks executed by different threads. Each block is executed by one thread.

- The different blocks are independent.

- Different blocks may be defined by the programmer using the ***SECTION*** directive inside a ***SECTIONS*** construct.

OpenMP
Work Sharing – SECTIONS directive

- All ***SECTION*** directives should be defined inside the lexical scope of a ***SECTIONS*** directive.

- There is an implicit barrier at the end of the ***SECTIONS*** construct unless a ***NOWAIT*** clause is specified.

- The different clauses that can be used in a ***SECTIONS*** directive are:
  - ✓ Private
  - ✓ Firstprivate
  - ✓ Lastprivate
  - ✓ Reduction

OpenMP
Work Sharing – SECTIONS directive

```
#include <stdio.h>
#include <omp.h>

int main()
{
  int   rank;

  #pragma omp parallel private(rang)
  {
      rank=omp_get_thread_num();
      #pragma omp sections nowait
      {
       #pragma omp section
       {
           printf("[Thread %d] \n",
   rank);
       }
       #pragma omp section
       {
           printf("[Thread %d] \n",
   rank);
       }
      }
  }
  return 0;
}
```

```
> gcc …  -fopenmp -o omp omp.c
> export OMP_NUM_THREADS=8
> ./omp

[Thread 7]
[Thread 0]
```

OpenMP
Exclusive Execution – MASTER directive

- The ***MASTER*** construct specifies that the associated structured block is executed by only the thread master (thread 0).
- No clauses can be used with this directive.
- There is no implicit barrier at the end of the ***MASTER*** directive.

OpenMP
Exclusive Execution – MASTER directive

```
#include <stdio.h>
#include <omp.h>

int main()
{
    int rank;
    int a;

    #pragma omp parallel
  private(a,rank)
    {
        a = 50000;

        #pragma omp master
        {
            a = -50000;
        }

        rank=omp_get_thread_num();
        printf("Rank : %d ; A =
  %d\n",rank,a);
    }
    return 0;
}
```

```
> gcc …  -fopenmp -o omp omp.c
> export OMP_NUM_THREADS=8
> ./omp

 Rank : 6 ; A = 50000
 Rank : 0 ; A = -50000
 Rank : 3 ; A = 50000
 Rank : 4 ; A = 50000
 Rank : 1 ; A = 50000
 Rank : 5 ; A = 50000
 Rank : 7 ; A = 50000
 Rank : 2 ; A = 50000
```