OpenMP

(Shared memory Parallel programming Model)

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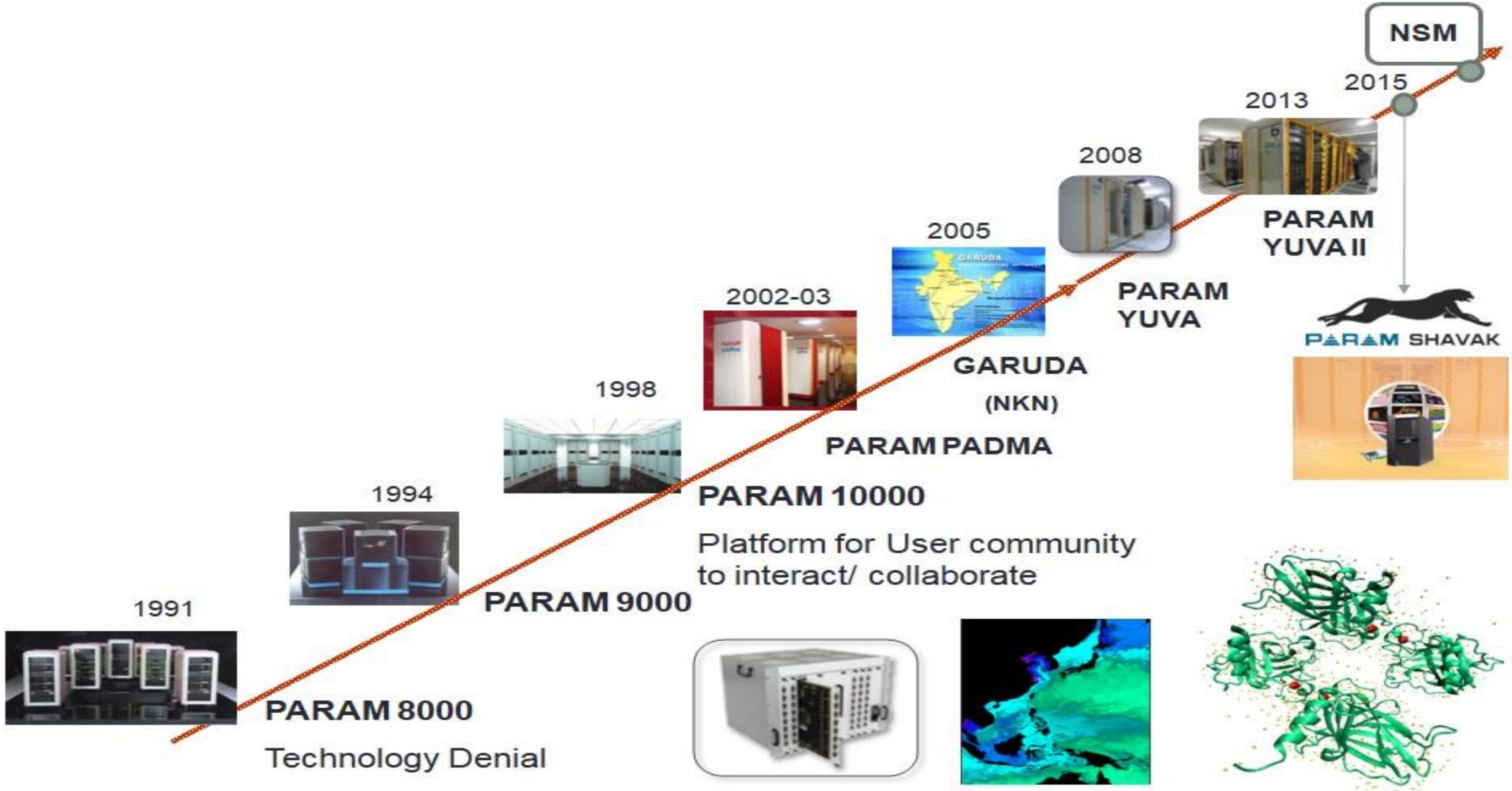
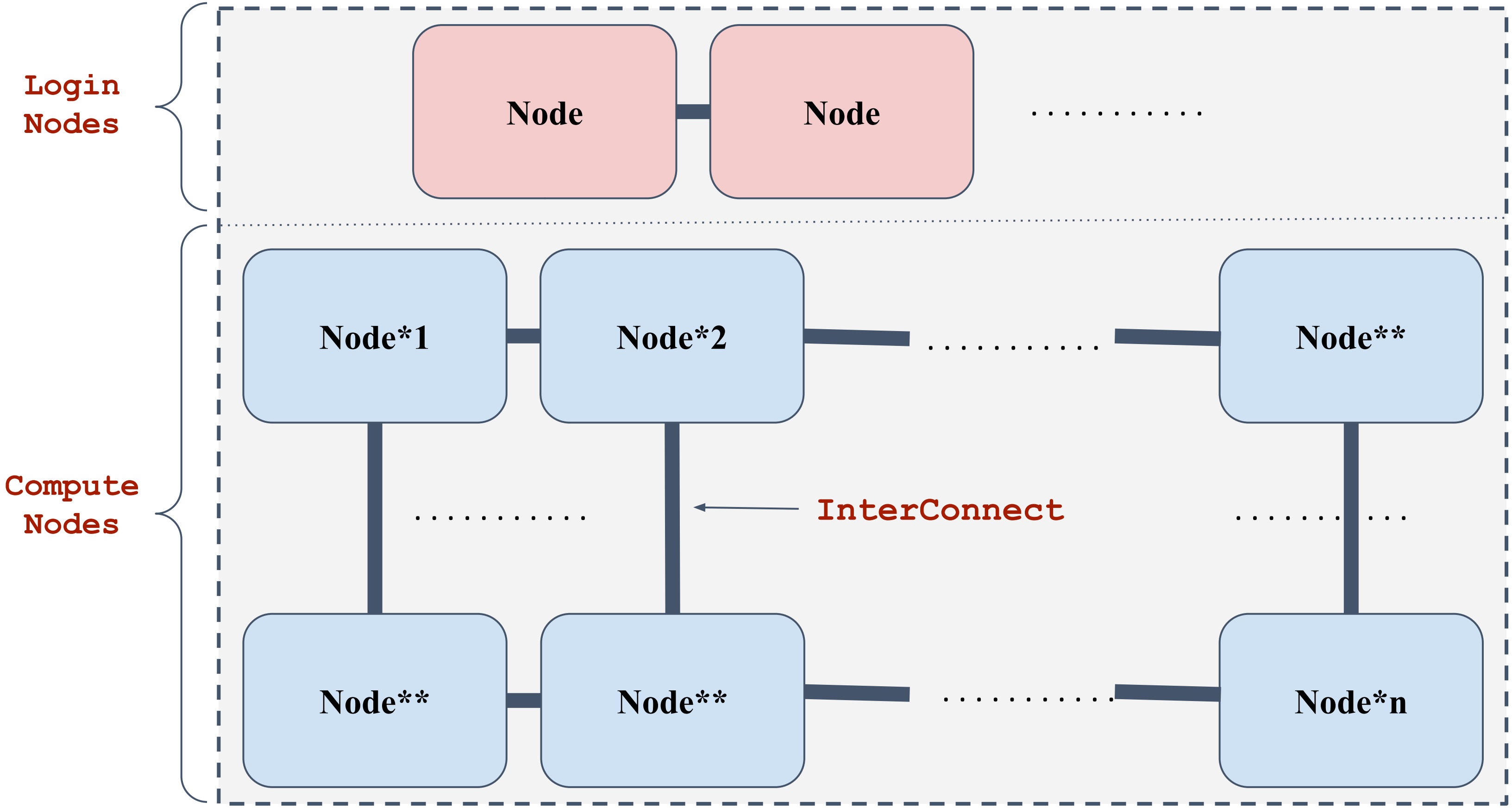
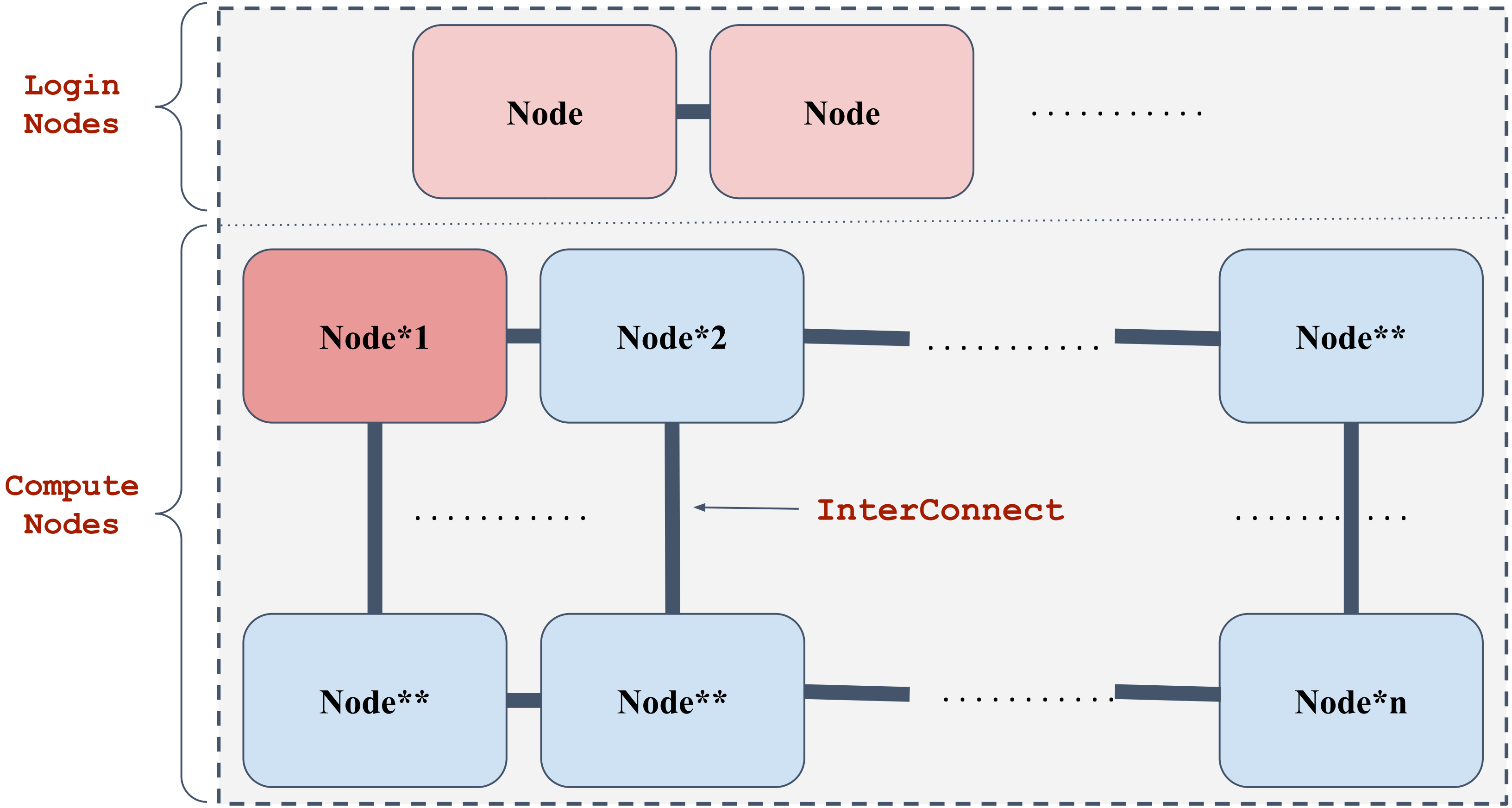

NSM
2015
2013
PARAM
YUVA II
2008
PARAM
YUVA
PARAM SHAVAK
2005
GARUDA
GARUDA
(NKN)
2002-03
PARAM PADMA
1998
PARAM 10000
Platform for User community
to interact/ collaborate
1994
PARAM 9000
1991
PARAM 8000
Technology Denial

HPC Cluster


Login
Nodes
Node
Node
Compute
Nodes
Node*1
Node*2
Node**
InterConnect
Node**
Node**
Node*n

HPC Cluster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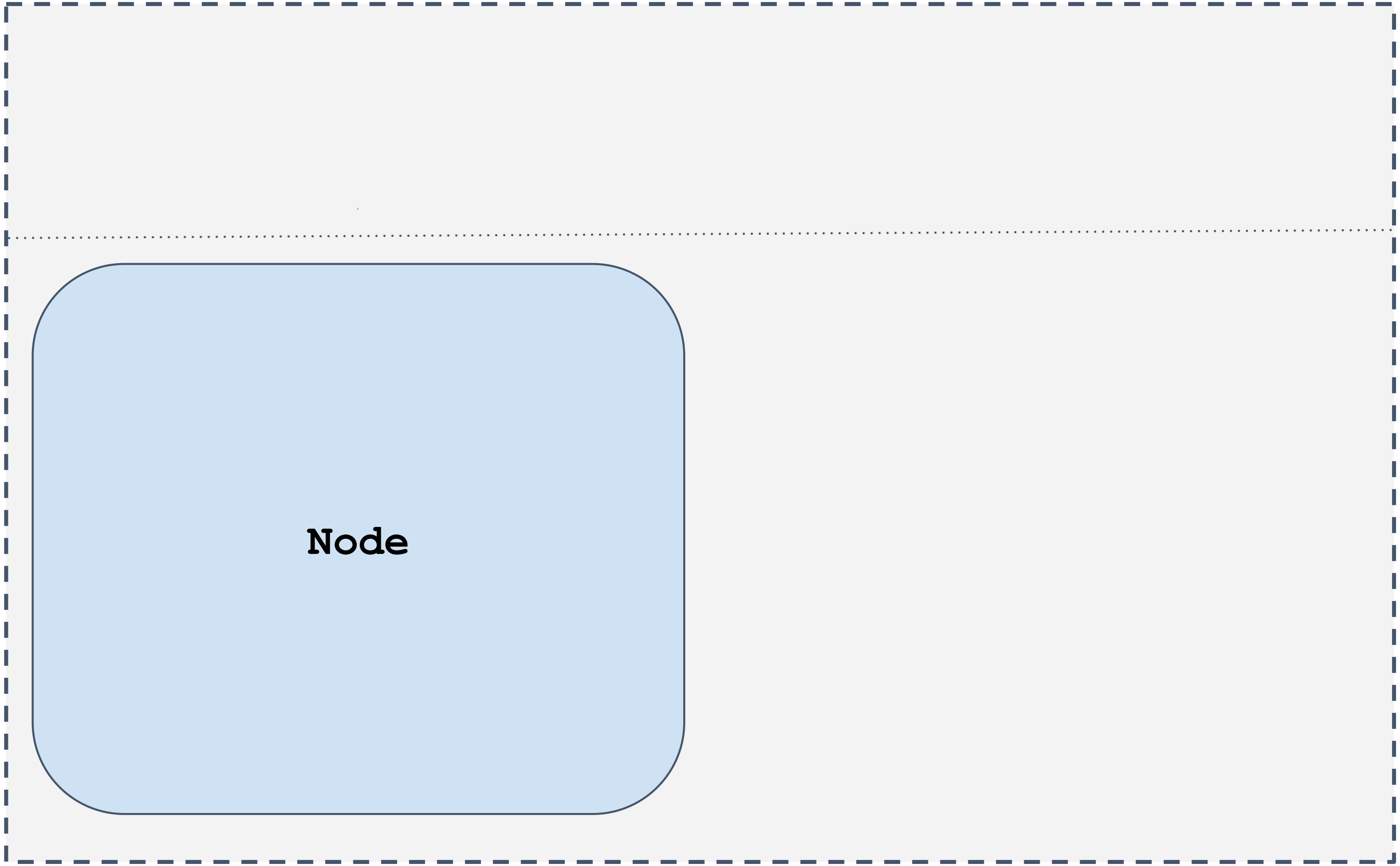
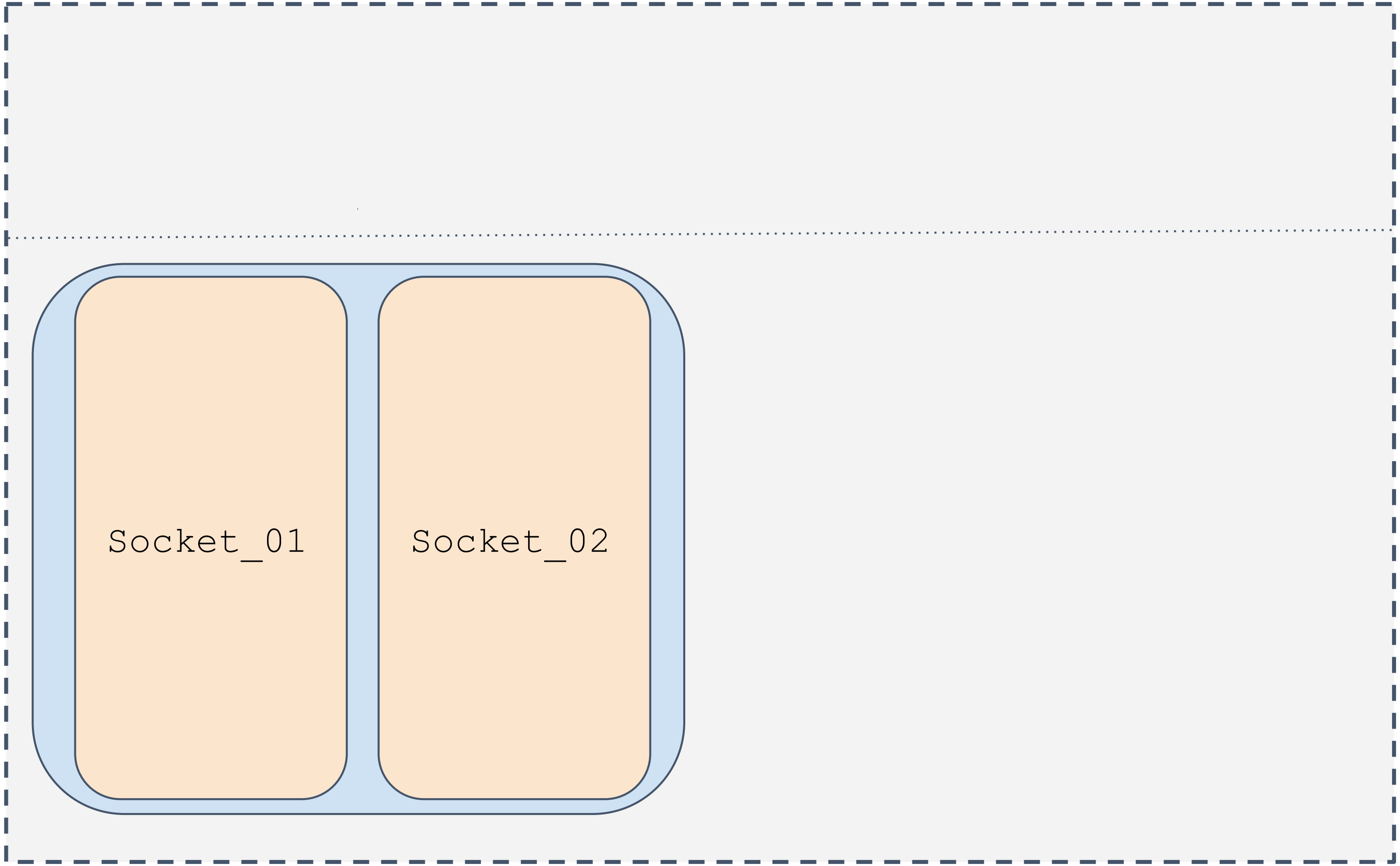
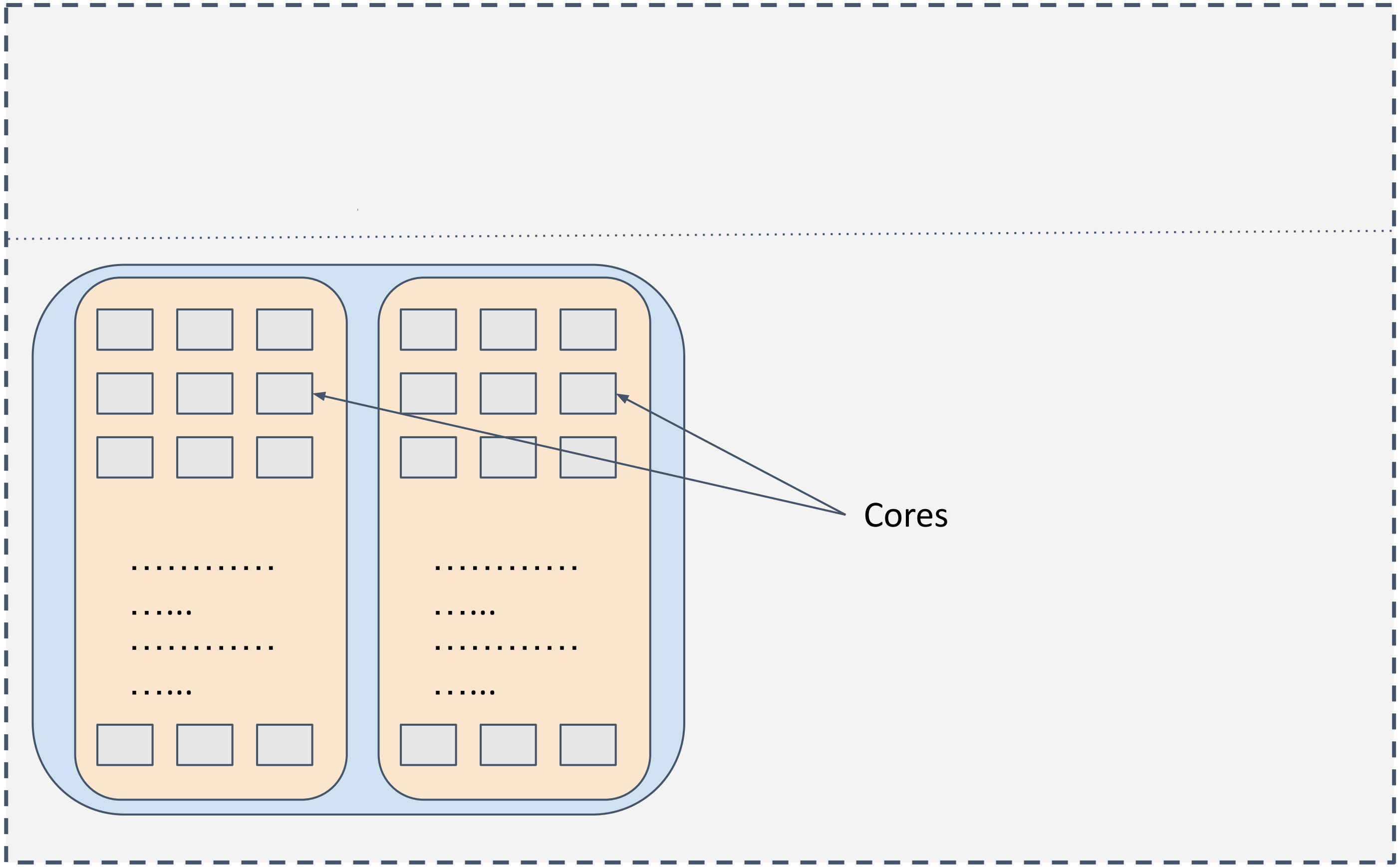
HPC Cluster



HPC Cluster



HPC Cluster

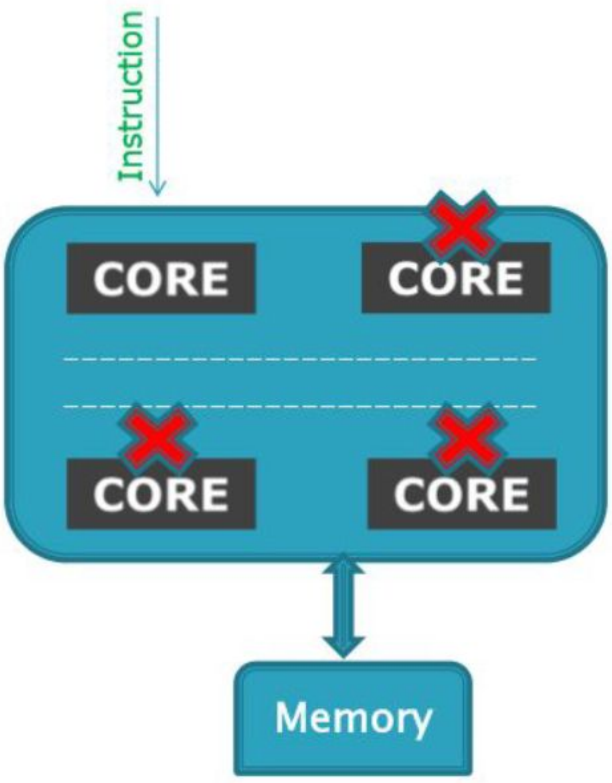


Program Execution ?

- When you run sequential program
  - Instructions executed in serial
  - Other cores are idle

- Waste of available resource...

- We want all cores to be used to execute program.
  - How ?



Program Execution ?

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  - Instructions executed in serial
  - Other cores are idle
- Waste of available resource...
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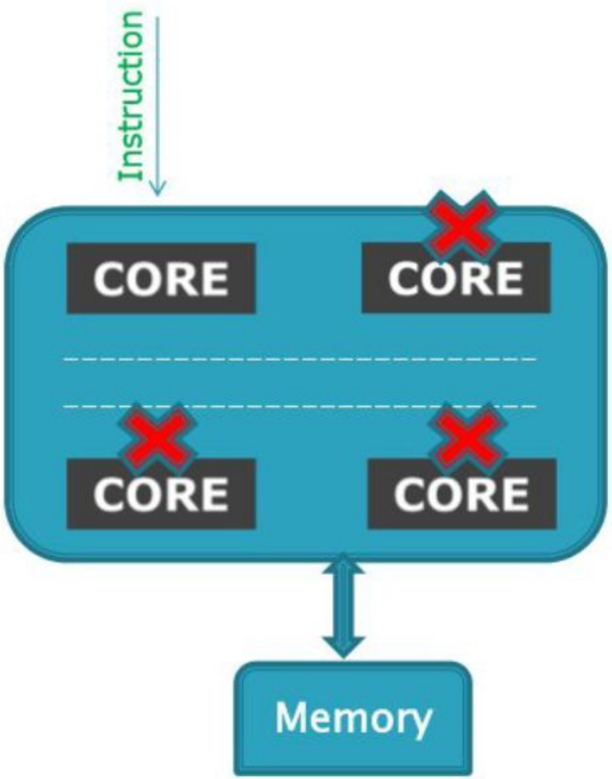
Parallel Programming Models



Program Execution ?

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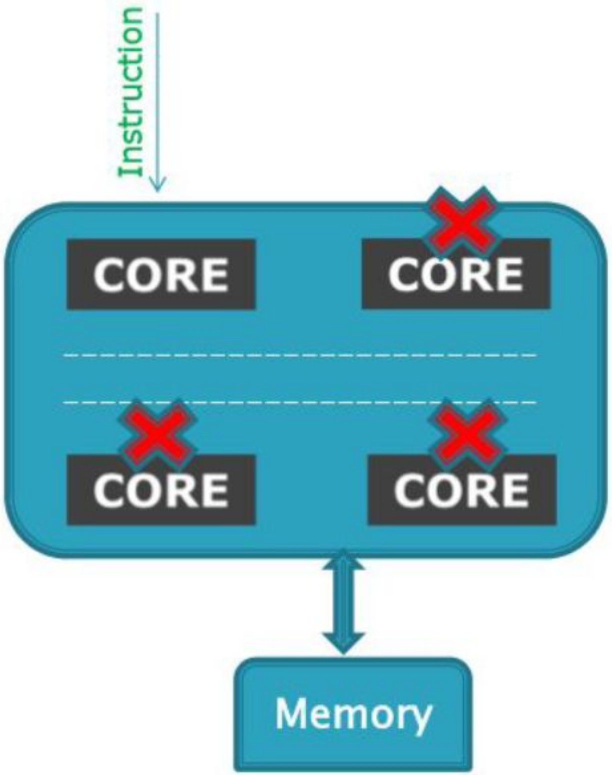
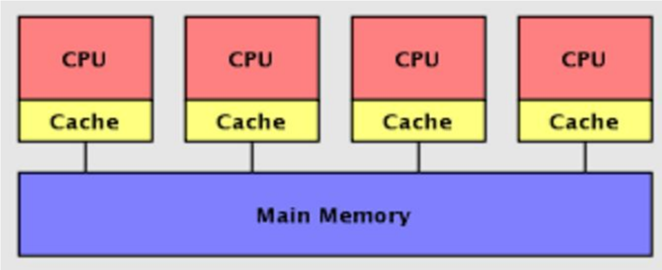


Parallel Programming Models

- **Shared Memory**
- **Distributed Memory**

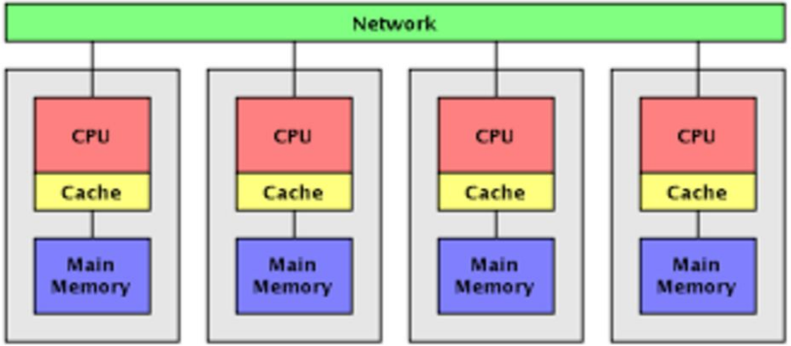
Parallel Programming Models

❑ Shared-memory Model



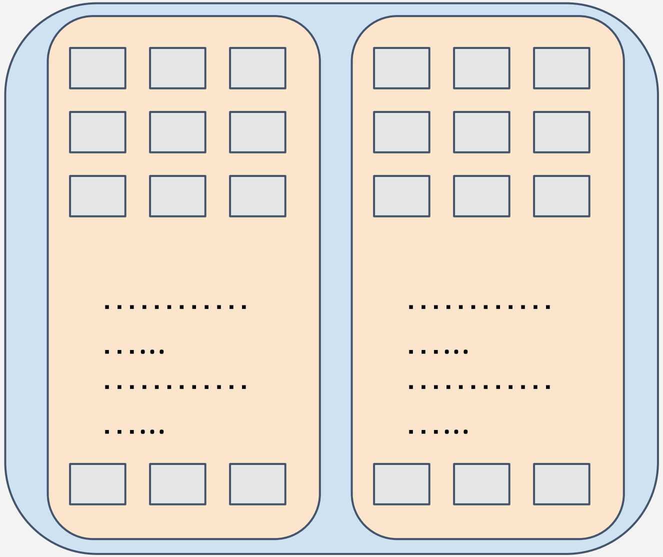
- ❖ OpenMP

❑ Distributed-memory Model



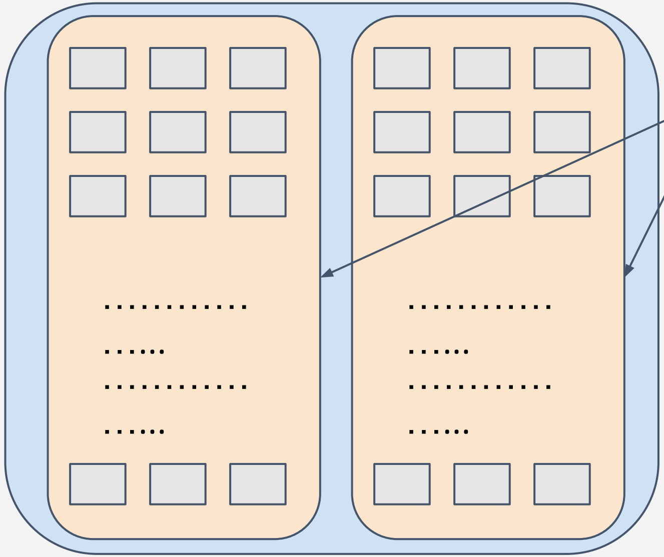
- ❖ MPI - Message Passing Interface

Shared Memory Programming Models



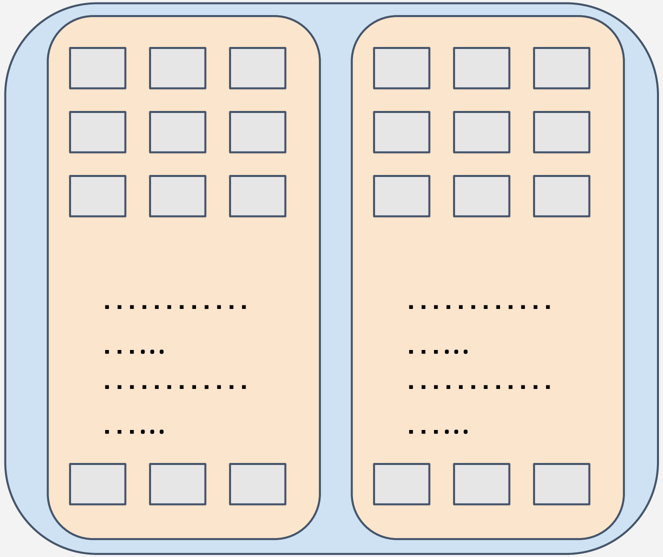
Shared Memory System

Shared Memory Programming Models

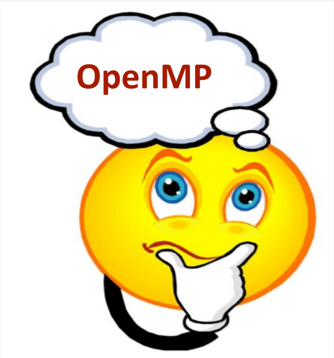


How you will utilize all the cores efficiently ?

Shared Memory Programming Models



How you will utilize all the cores efficiently ?



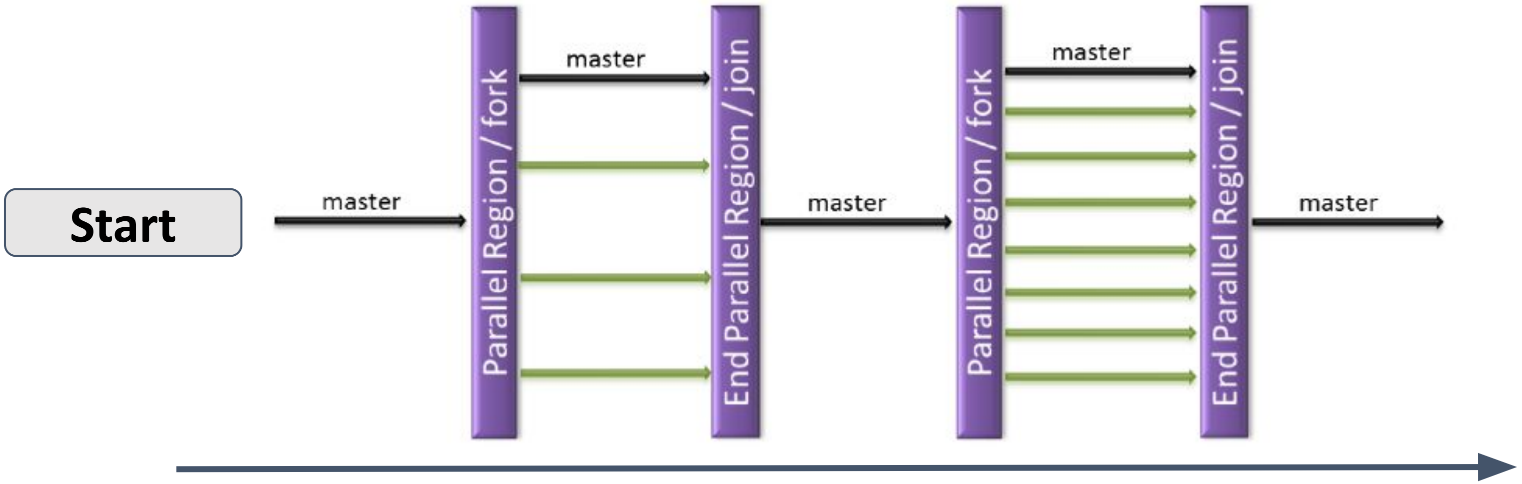
OpenMP

- Portable shared memory programming

- Easy to learn
  - OpenMP specific commands in source codes are processed by the compiler
  - OpenMP functionality is switched on by a compiler specific option

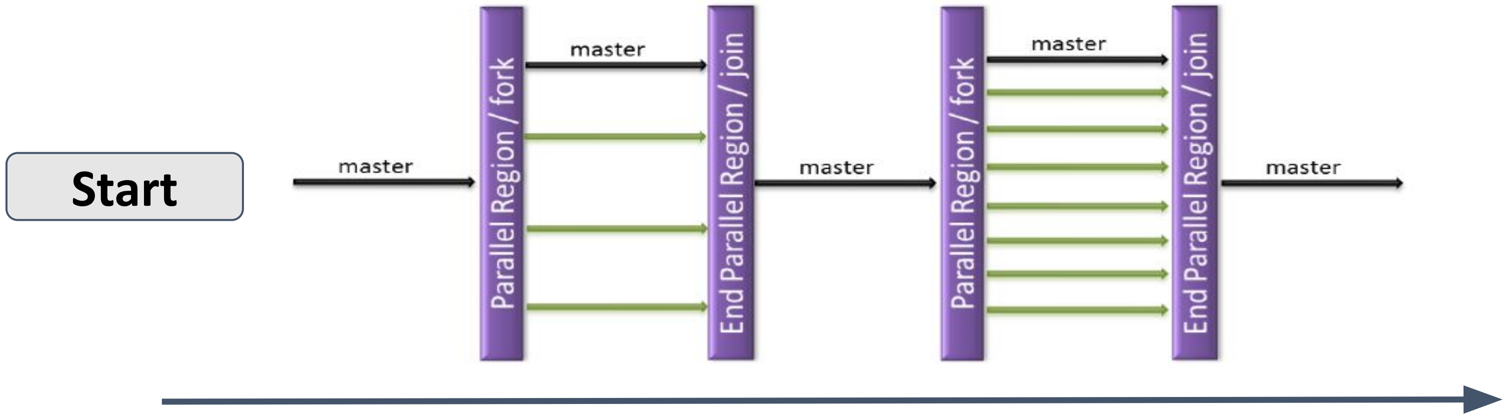
- Parallelization is fully controlled by programmer
  - Directives for Fortran 77/90 and pragmas for C/C++
  - Run-time library routines
  - Environment variables

OpenMP : Fork-Join Programming model



- ➢ Master Thread (MT) executes sequentially the program
- ➢ A team of threads is being generated when MT encounters a Parallel Region (PR)
- ➢ All but the MT are being destroyed at the end of a PR

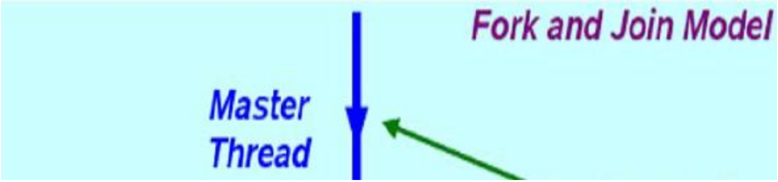
OpenMP : Fork-Join Programming model



➢ **Threads**

- Threads are numbered from 0 to (n - 1), n is the number of threads
- omp_get_num_threads gives the number of available threads
- omp_get_thread_num tells the thread, its number
- A single program with several threads is able to handle several tasks concurrently
- Each thread has its own **stack and registers**

OpenMP : Execution model



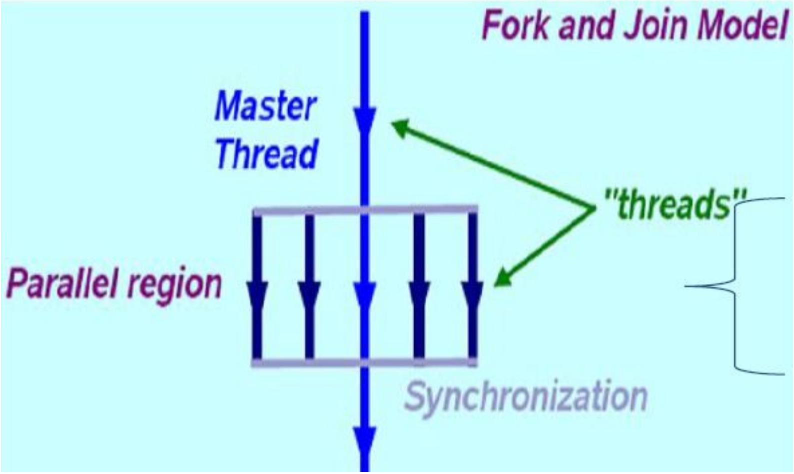

```
main (..)
{


#pragma omp parallel
{
      ......
      ......
}


#pragma omp parallel
{
      ......
      ......
}


}
```

OpenMP : Execution model



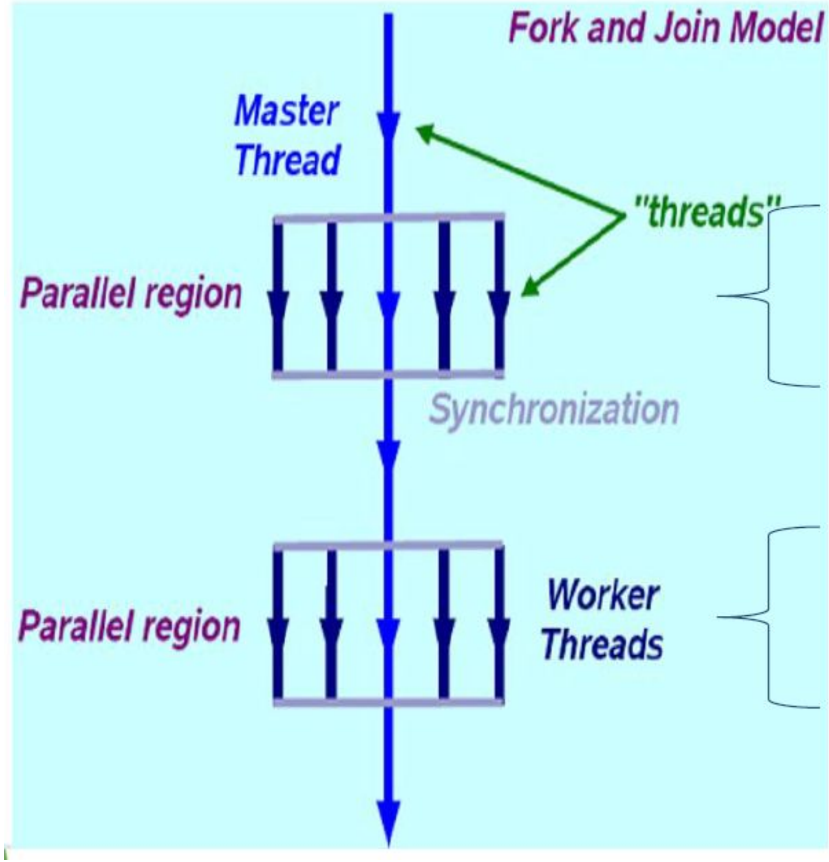

```
main (..)
{


#pragma omp parallel
{
      ......
      ......
}


#pragma omp parallel
{
      ......
      ......
}


}
```

OpenMP : Execution model




```
main (..)
{

#pragma omp parallel
{
    ......
    ......
}

#pragma omp parallel
{
    ......
    ......
}

}
```

Sample Program

```
#include <stdio.h>

int main(int argc, char* argv[])
{

    printf("Hello, Om ! \n");


}
```

Sample Program

```c
#include <stdio.h>

int main(int argc, char* argv[])
{

    printf("Hello, Om ! \n");


}
```

```
$ gcc hello_serial.c -o hello_serial
```

Sample Program

```
#include <stdio.h>

int main(int argc, char* argv[])
{

    printf("Hello, Om ! \n");


}
```

```
$ gcc hello_serial.c -o hello_serial
```

```
$ ./hello_serial

Hello, Om
```

Sample Program

```
#include <stdio.h>

int main(int argc, char* argv[])
{

    printf("Hello, Om ! \n");


}
```

```
#include <stdio.h>
#include <omp.h>
int main(int argc, char* argv[])
{
     #pragma omp parallel
      printf("Hello Om, I am thread =
%d\n", omp_get_thread_num()) ;

}
```

```
$ gcc hello_serial.c -o hello_serial
```

```
$ ./hello_serial

Hello, Om
```

Sample Program

```c
#include <stdio.h>

int main(int argc, char* argv[])
{

    printf("Hello, Om ! \n");


}
```

```c
#include <stdio.h>
#include <omp.h>
int main(int argc, char* argv[])
{
     #pragma omp parallel
      printf("Hello Om, I am thread = 
%d\n", omp_get_thread_num()) ;

}
```

$ gcc hello_serial.c -o hello_serial

$ gcc **-fopenmp** hello_parallel.c -o hello_parallel

$ ./hello_serial

Hello, Om

Sample Program

```
#include <stdio.h>

int main(int argc, char* argv[])
{

    printf("Hello, Om ! \n");


}
```

```
#include <stdio.h>
#include <omp.h>
int main(int argc, char* argv[])
{
     #pragma omp parallel
      printf("Hello Om, I am thread =
%d\n", omp_get_thread_num()) ;

}
```

```
$ gcc hello_serial.c -o hello_serial
```

```
$ gcc -fopenmp hello_parallel.c -o hello_parallel
```

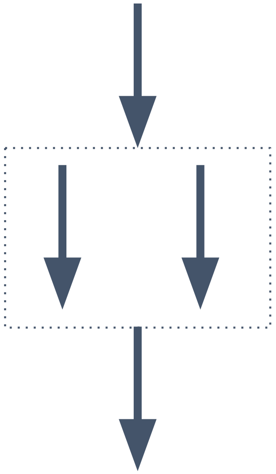
```
$ ./hello_serial

Hello, Om
```

```
$ export OMP_NUM_THREADS=2
$ ./hello_parallel

Hello Om, I am thread = 0
Hello Om, I am thread = 1
```

Sample Program



```
#include <stdio.h>
#include <omp.h>
int main(int argc, char* argv[])
{
    #pragma omp parallel
     printf("Hello Om, I am thread =
%d\n", omp_get_thread_num()) ;

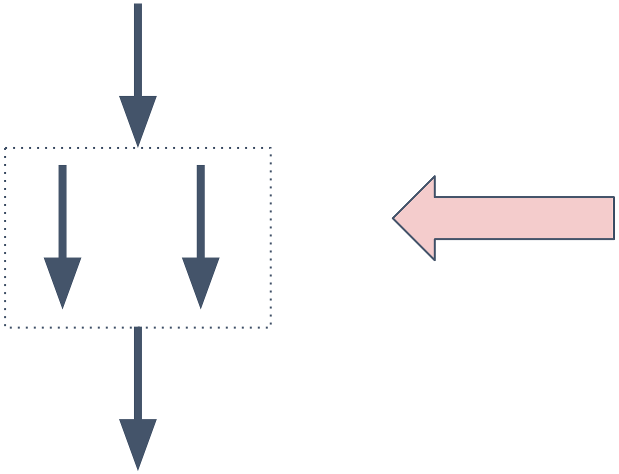
}
```

```
$ gcc -fopenmp hello_parallel.c -o hello_parallel
```

```
$ export OMP_NUM_THREADS=2
$ ./hello_parallel

Hello Om, I am thread = 0
Hello Om, I am thread = 1
```

Sample Program



```
#include <stdio.h>
#include <omp.h>
int main(int argc, char* argv[])
{
    #pragma omp parallel
     printf("Hello Om, I am thread = %d\n", omp_get_thread_num()) ;

}
```

```
$ gcc -fopenmp hello_parallel.c -o hello_parallel
```

```
$ export OMP_NUM_THREADS=2
$ ./hello_parallel

Hello Om, I am thread = 0
Hello Om, I am thread = 1
```

Threads

```
#include <stdio.h>
#include <omp.h>
int main(int argc, char* argv[])
{
     #pragma omp parallel
      printf("Hello Om, I am thread = %d\n", omp_get_thread_num()) ;

}
```

Method 1 : Environment Variable

OMP_NUM_THREADS

```
$ export OMP_NUM_THREADS=2
$ ./hello_parallel

Hello Om, I am thread = 0
Hello Om, I am thread = 1
```

Threads

```
#include <stdio.h>
#include <omp.h>
int main(int argc, char* argv[])
{
    omp_set_num_threads(4) ;
    #pragma omp parallel
     printf("Hello Om, I am thread = %d\n", omp_get_thread_num()) ;
}
```

Method 2 : Routine

omp_set_num_threads(int num_threads) ;

```
$ ./hello_parallel

Hello Om, I am thread = 1
Hello Om, I am thread = 0
Hello Om, I am thread = 3
Hello Om, I am thread = 2
```

Threads

```
#include <stdio.h>
#include <omp.h>
int main(int argc, char* argv[])
{
     omp_set_num_threads(4) ;
     #pragma omp parallel
      printf("Hello Om, I am thread = %d\n", omp_get_thread_num()) ;
}
```

Method 2 : Routine

`omp_set_num_threads(int num_threads) ;`

```
$ ./hello_parallel

Hello Om, I am thread = 1
Hello Om, I am thread = 0
Hello Om, I am thread = 3
Hello Om, I am thread = 2
```

Routines have higher priority than the environment variables !

Exercise

Write your first Parallel Program, with which you should be able to print your NAME from 4 underline cores !

Time : 3 min

Shared memory - scenario !

Shared memory - scenario !

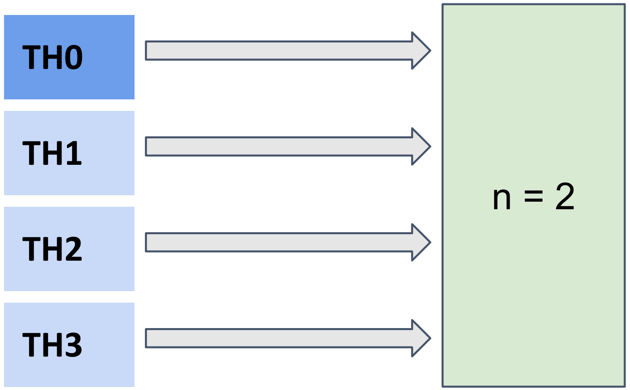
Let's understand different scenarios with different use cases !

Data variable scope

How data variables will be shared among different threads of parallel execution ?

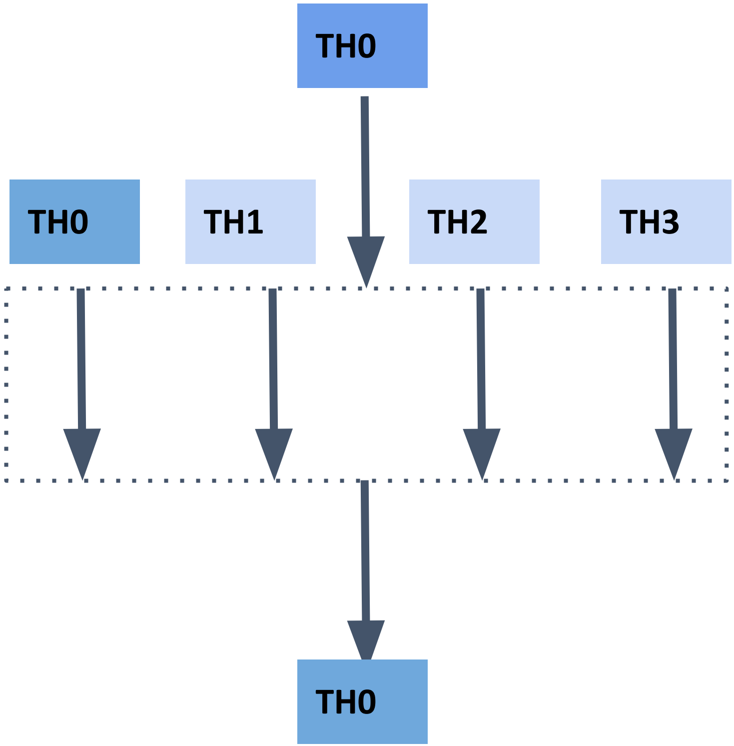
Scope of data variables : shared

- Data objects (variables) can be **shared** or **private**
- **Shared**
  - By **default** almost all variables are **shared**
  - Accessible to all threads
  - **Single instance** in shared memory



Shared Instance

Int n=2



Example -1

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

int main(int argc, char* argv[])
{
int tid, sum=5 ;
#pragma omp parallel
{
  tid = omp_get_thread_num();
  sum = sum + tid;
  printf("Value at thread %d = %d \n", tid, sum) ;
}

printf("Value After parallel region, thread %d = %d \n", omp_get_thread_num(),
sum) ;
}
```

Example -1

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

int main(int argc, char* argv[])
{
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printf("Value After parallel region, thread %d = %d \n", omp_get_thread_num(),
sum) ;
}
```

What is expected output of the program ?

Example -1

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

int main(int argc, char* argv[])
{
int tid, sum=5 ;
#pragma omp parallel
{
  tid = omp_get_thread_num();
  sum = sum + tid;
  printf("Value at thread %d = %d \n", tid, sum) ;
}

printf("Value After parallel region, thread %d = %d \n", omp_get_thread_num(),
sum) ;
}
```

Every thread should add his thread-Id to a constant number and print

What is expected output of the program ?

Example -1

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

int main(int argc, char* argv[])
{
int tid, sum=5 ;
#pragma omp parallel
{
  tid = omp_get_thread_num();
  sum = sum + tid;
  printf("Value at thread %d = %d \n", tid, sum) ;
}

printf("Value After parallel region, thread %d = %d \n", omp_ r num(),
sum) ;
}
```

TH0	5
TH1	6
TH2	7
TH3	8

TH0	5

```
[om@shrestha1 SampleCodes]$ gcc -fopenmp variables.c
[om@shrestha1 SampleCodes]$ ./a.out
Value at thread 2 = 7
Value at thread 1 = 11
Value at thread 0 = 5
Value at thread 3 = 10
Value After paralle region, thread 0 = 11
[om@shrestha1 SampleCodes]$
```

Is it expected result ?

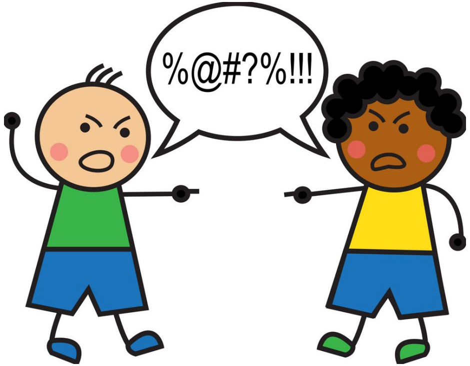
```
[om@shrestha1 SampleCodes]$ gcc -fopenmp variables.c
[om@shrestha1 SampleCodes]$ ./a.out
Value at thread 2 = 7
Value at thread 1 = 11
Value at thread 0 = 5
Value at thread 3 = 10
Value After paralle region, thread 0 = 11
[om@shrestha1 SampleCodes]$
```

```
[om@shrestha1 SampleCodes]$ gcc -fopenmp variables.c
[om@shrestha1 SampleCodes]$ ./a.out
Value at thread 2 = 7
Value at thread 1 = 11
Value at thread 0 = 5
Value at thread 3 = 10
Value After paralle region, thread 0 = 11
[om@shrestha1 SampleCodes]$
```

So, what is the problem ?

```
[om@shrestha1 SampleCodes]$ gcc -fopenmp variables.c
[om@shrestha1 SampleCodes]$ ./a.out
Value at thread 2 = 7
Value at thread 1 = 11
Value at thread 0 = 5
Value at thread 3 = 10
Value After paralle region, thread 0 = 11
[om@shrestha1 SampleCodes]$
```

Race Condition



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[om@shrestha1 SampleCodes]$ ./a.out
Value at thread 2 = 7
Value at thread 1 = 11
Value at thread 0 = 5
Value at thread 3 = 10
Value After paralle region, thread 0 = 11
[om@shrestha1 SampleCodes]$
```

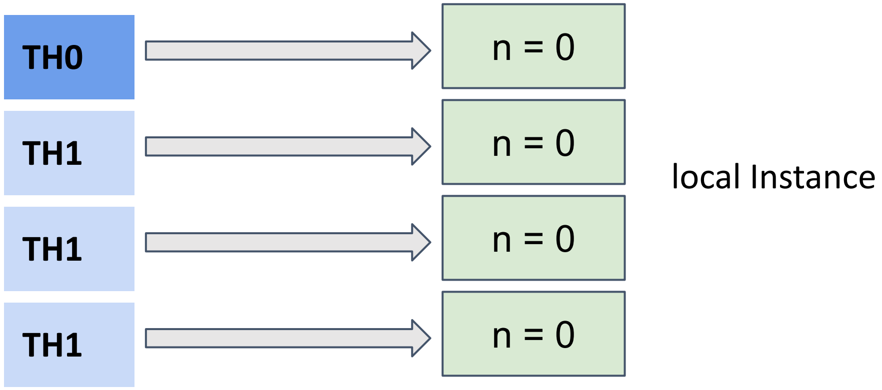
Learning : We need to be careful while declaring the scope of variables. The variables which is going to update in parallel region, should give special attention while writing a parallel program in shared memory system.

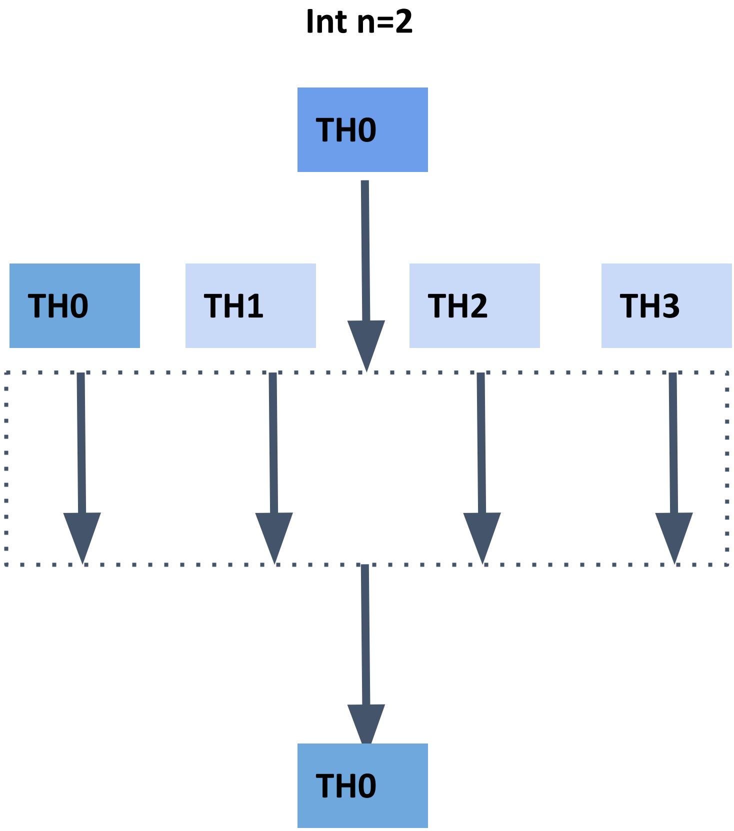
```
[om@shrestha1 SampleCodes]$ gcc -fopenmp variables.c
[om@shrestha1 SampleCodes]$ ./a.out
Value at thread 2 = 7
Value at thread 1 = 11
Value at thread 0 = 5
Value at thread 3 = 10
Value After paralle region, thread 0 = 11
[om@shrestha1 SampleCodes]$
```

Solution ?

Scope of data variables : private

- **private**
  - Each thread allocates its **own private copy of the data**
  - Only **exists during the execution** of a parallel region!
  - Value **undefined/0** upon **entry & exit** of parallel region





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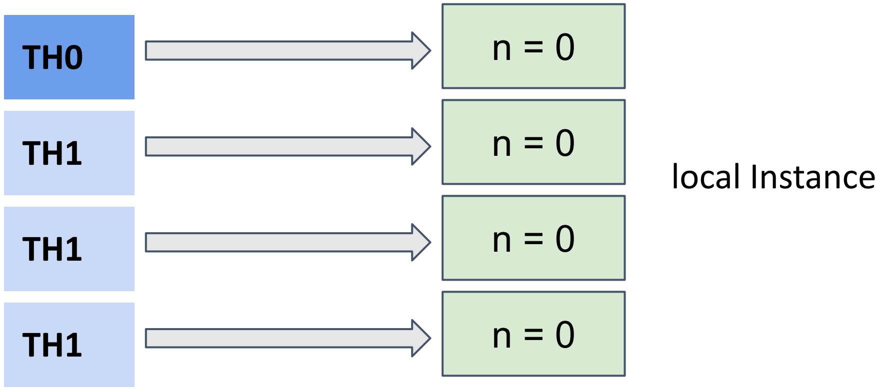
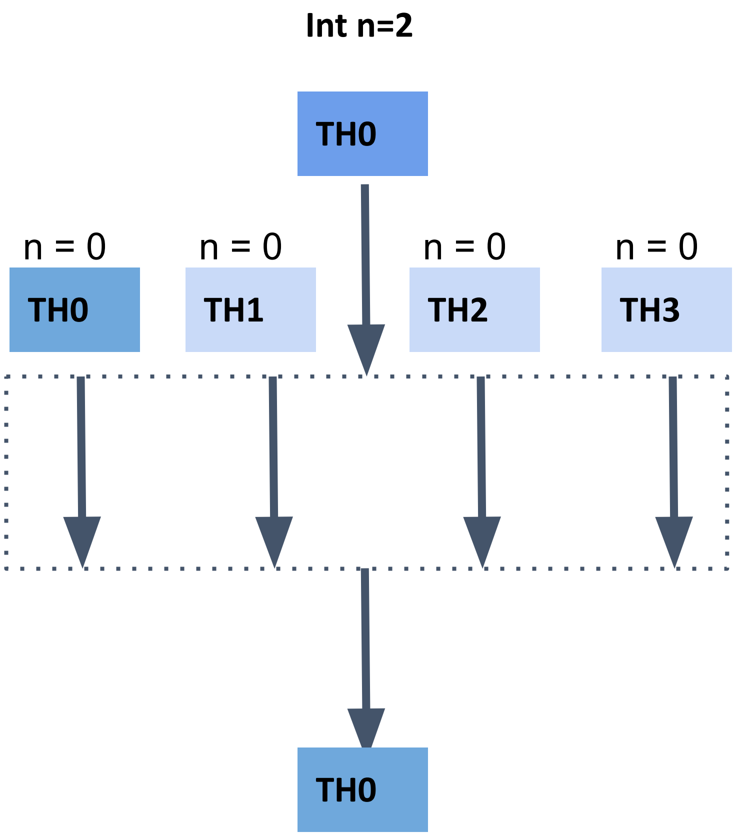




Example - 2

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

int main(int argc, char* argv[])
{
int tid, sum=5 ;
#pragma omp parallel private( ? )
{
  tid = omp_get_thread_num();
  sum = sum + tid;
  printf("Value at thread %d = %d \n", tid, sum) ;
}

printf("Value After parallel region, thread %d = %d \n", omp_get_thread_num(), sum) ;
}
```

Example - 2

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

int main(int argc, char* argv[])
{
int tid, sum=5 ;
#pragma omp parallel private(sum)
{
  tid = omp_get_thread_num();
  sum = sum + tid;
  printf("Value at thread %d = %d \n", tid, sum) ;
}

printf("Value After parallel region, thread %d = %d \n", omp_get_thread_num(), sum) ;
}
```

What will be the output ?

Example - 2

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

int main(int argc, char* argv[])
{
int tid, sum=5 ;
#pragma omp parallel private(sum)
{
  tid = omp_get_thread_num();
  sum = sum + tid;
  printf("Value at thread %d = %d \n", tid, sum) ;
}

printf("Value After parallel region, thread %d = %d \n", omp_get_thread_num(), sum) ;
}
```

What will be the output ?

```
[om@shrestha1 SampleCodes]$ gcc -fopenmp variables.c
[om@shrestha1 SampleCodes]$ ./a.out
Value at thread 0 = 0
Value at thread 2 = 2
Value at thread 1 = 1
Value at thread 3 = 3
Value After paralle region, thread 0 = 5
[om@shrestha1 SampleCodes]$
```

Observe the output and try to understand the difference !

shared

```
[om@shrestha1 SampleCodes]$ gcc -fopenmp variables.c
[om@shrestha1 SampleCodes]$ ./a.out
Value at thread 2 = 7
Value at thread 1 = 11
Value at thread 0 = 5
Value at thread 3 = 10
Value After paralle region, thread 0 = 11
[om@shrestha1 SampleCodes]$
```

```
[om@shrestha1 SampleCodes]$ gcc -fopenmp variables.c
[om@shrestha1 SampleCodes]$ ./a.out
Value at thread 0 = 0
Value at thread 2 = 2
Value at thread 1 = 1
Value at thread 3 = 3
Value After paralle region, thread 0 = 5
[om@shrestha1 SampleCodes]$
```

private

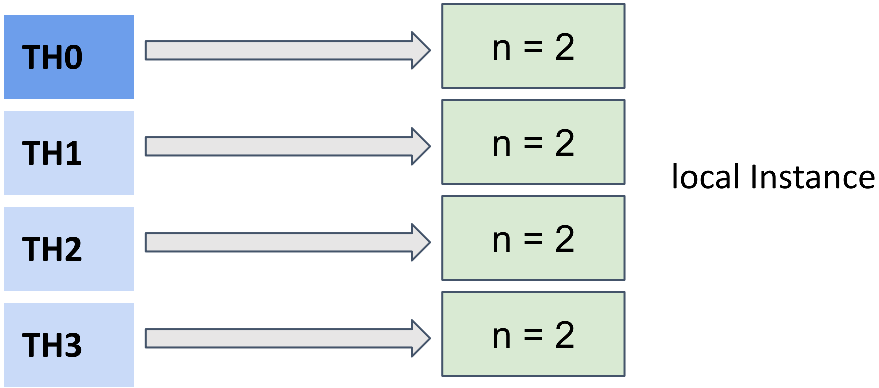
```
[om@shrestha1 SampleCodes]$ gcc -fopenmp variables.c
[om@shrestha1 SampleCodes]$ ./a.out
Value at thread 0 = 0
Value at thread 2 = 2
Value at thread 1 = 1
Value at thread 3 = 3
Value After paralle region, thread 0 = 5
[om@shrestha1 SampleCodes]$
```

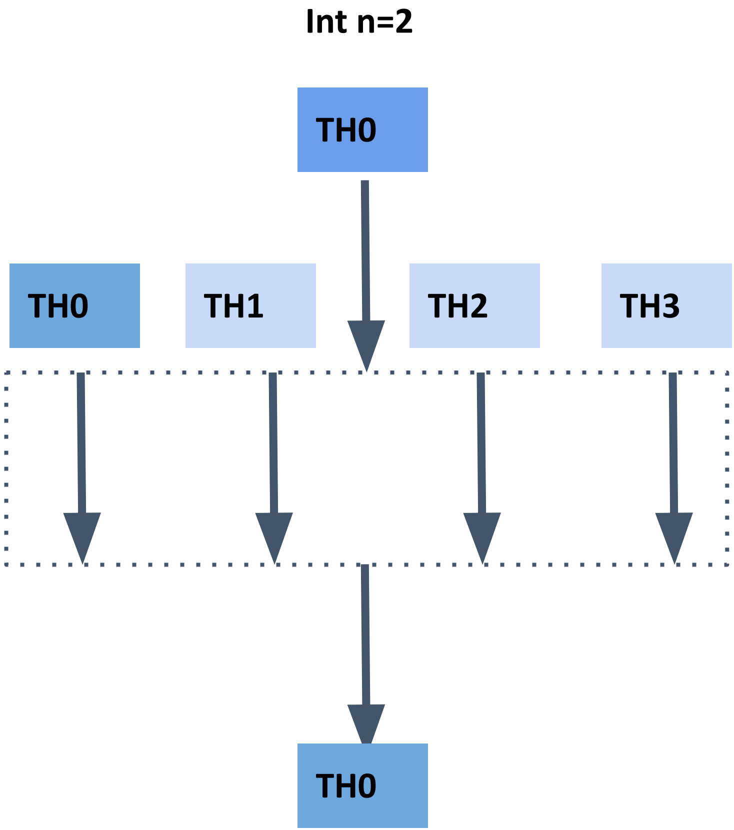
Learning :

- In case of private, the value of variable is **undefined/0** upon entry & exit of parallel region
- Only **exists during the execution** of a parallel region!

Scope of data variables : firstprivate

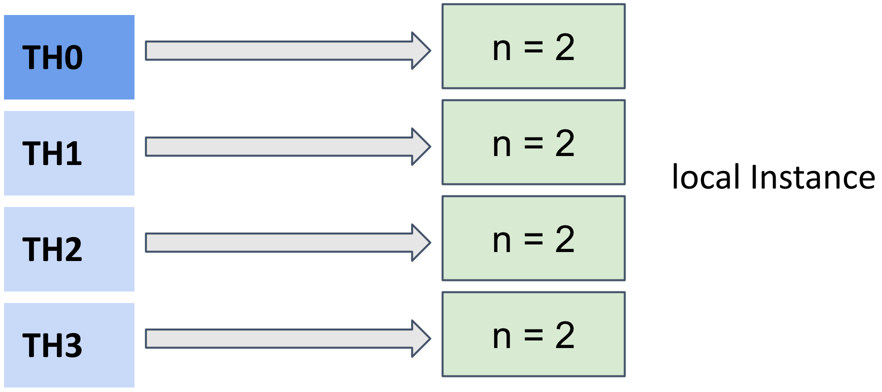
- **firstprivate**
  - Then each thread allocates its **own private copy of the data**
  - Only **exists during the execution** of a parallel region!
  - Additionally, get initialized with **value of original variable** (at entry)

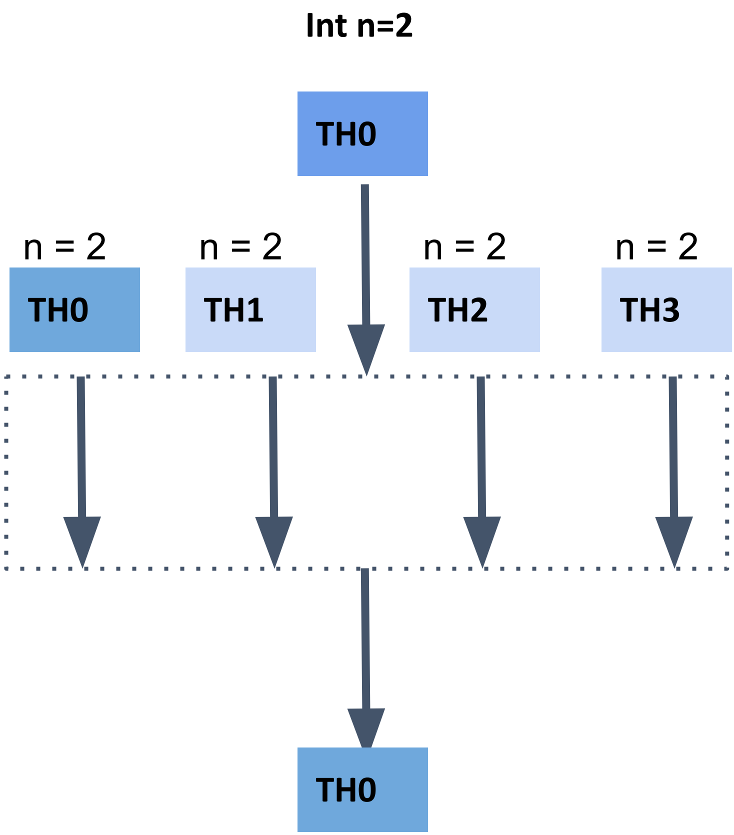




Scope of data variables : firstprivate

- **firstprivate**
  - Then each thread allocates its **own private copy of the data**
  - Only **exists during the execution** of a parallel region!
  - Additionally, get initialized with **value of original variable** (at entry)





Example - 3

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

int main(int argc, char* argv[])
{
int tid, sum=5 ;
#pragma omp parallel firstprivate(sum)
{
  tid = omp_get_thread_num();
  sum = sum + tid;
  printf("Value at thread %d = %d \n", tid, sum) ;
}

printf("Value After parallel region, thread %d = %d \n", omp_get_thread_num(), sum) ;
}
```

What will be the output ?

Example - 3

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

int main(int argc, char* argv[])
{
int tid, sum=5 ;
#pragma omp parallel firstprivate(sum)
{
  tid = omp_get_thread_num();
  sum = sum + tid;
  printf("Value at thread %d = %d \n", tid, sum) ;
}

printf("Value After parallel region, thread %d = %d \n", omp_get_thread_num(), sum) ;
}
```

What will be the output ?

```
[om@shrestha1 SampleCodes]$ gcc -fopenmp variables.c
[om@shrestha1 SampleCodes]$ ./a.out
Value at thread 0 = 5
Value at thread 3 = 8
Value at thread 2 = 7
Value at thread 1 = 6
Value After paralle region, thread 0 = 5
[om@shrestha1 SampleCodes]$
```

```
[om@shrestha1 SampleCodes]$ gcc -fopenmp variables.c
[om@shrestha1 SampleCodes]$ ./a.out
Value at thread 0 = 5
Value at thread 3 = 8
Value at thread 2 = 7
Value at thread 1 = 6
Value After paralle region, thread 0 = 5
[om@shrestha1 SampleCodes]$
```

Learning :

- In case of firstprivate, the value of variable get initialized with **value of original variable** at the entry of parallel region
- Only **exists during the execution** of a parallel region!

```
[om@shrestha1 SampleCodes]$ gcc -fopenmp variables.c
[om@shrestha1 SampleCodes]$ ./a.out
Value at thread 0 = 5
Value at thread 3 = 8
Value at thread 2 = 7
Value at thread 1 = 6
Value After paralle region, thread 0 = 5
[om@shrestha1 SampleCodes]$
```

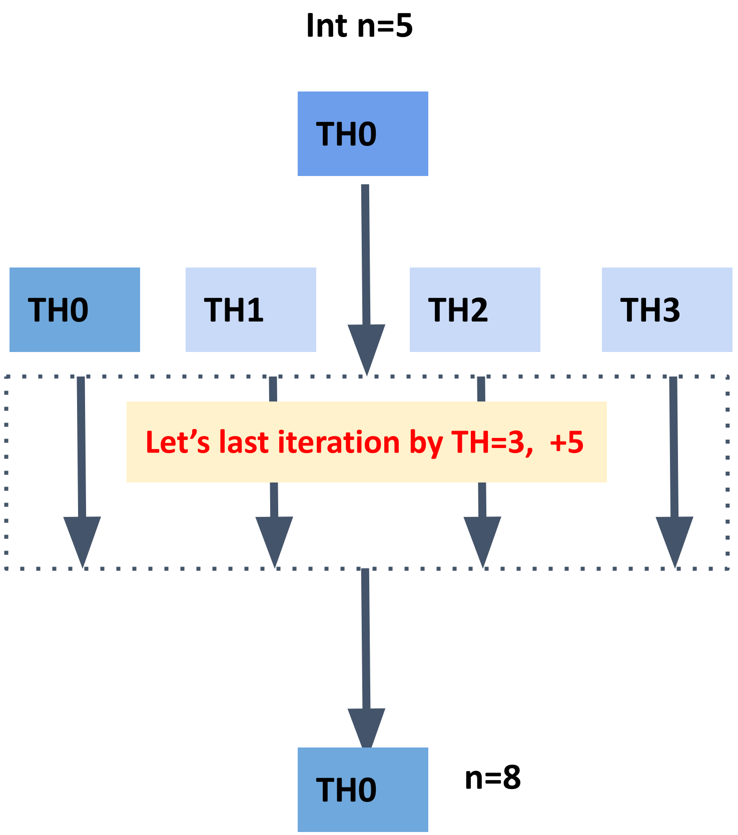
TH0	5
TH1	6
TH2	7
TH3	8

TH0	5

...achieved the initial target !

Scope of data variables : lastprivate

- **lastprivate**
  - Declares variables as private.
  - Corresponding **shared variable after parallel region gets value from that thread that finished the parallel region.**
  - It updates shared value after exit.
  - The meaning of lastprivate, is to assign **"the sequentially last iteration of the associated loops, or the lexically last section construct [...] to the original list item."**
  - Hence, there it no meaning for a pure parallel construct. It would not be a good idea to use a meaning like "the last thread to exit the parallel construct" - that would be a race condition.



Work Sharing

How the work will be distributed among threads of parallel execution ?

Work Sharing

How the work will be distributed among threads of parallel execution ?

Let's try to understand with different practical examples !

Work Sharing : Loops (parallel for loop)

Work load should be balanced, e.g. each thread should need the same period of time to handle its task

- Iterations of a parallel loop are executed in parallel by all threads of the current team of threads.
- The calculations inside an iteration must not depend on other iterations > responsibility of the programmer
- A schedule determines how iterations are divided among the threads
  - Specified by “schedule” parameter
- The form of the loop has to allow computing the number of iterations prior to entry into the loop > e.g., no WHILE loops

Work Sharing : Scheduling

- Scheduling Strategies
  - Distribution of iterations occurs in chunks
  - Chunks may have different sizes
  - Chunks are assigned either statically or dynamically
  - There are different assignment algorithms (types)
    - static
    - dynamic
    - guided
    - runtime

Work Sharing : Scheduling

1. Static

- ➢ Distribution is done at loop-entry time based on
  - Number of threads
  - Total number of iterations
- ➢ Less flexible
- ➢ Almost no scheduling overhead
- ➢ Workload is more or less the same for each iteration

Types :

- ➢ static without chunk size :
  - One chunk of iterations per thread, all chunks (nearly) equal size
- ➢ static with chunk size
  - Chunks with specified size are assigned in round-robin fashion

Example - 4

Write a Parallel C program where the iterations of a loop should scheduled statically across the team of threads. A thread should perform CHUNK iterations at a time before being scheduled for the next CHUNK of work.

Static

```
#include <omp.h>
#include <stdio.h>
#include <stdlib.h>
#define CHUNKSIZE   1
#define N   4

int main (int argc, char *argv[])
{
int nthreads, tid, i, chunk;
float a[N], b[N], c[N];

/* Some initializations */
for (i=0; i < N; i++)
  a[i] = b[i] = i * 1.0;
chunk = CHUNKSIZE;
```

```
#pragma omp parallel private(i,tid) //start
  {
  tid = omp_get_thread_num();
  if (tid == 0)
    {
    nthreads = omp_get_num_threads();
    printf("Number of threads = %d\n",
nthreads);
    }

  printf("Thread %d starting...\n",tid);
  #pragma omp for schedule(static,chunk)
  for (i=0; i<N; i++)
   {
   c[i] = a[i] + b[i];
   printf("Thread %d: c[%d]=%f\n",tid,i,c[i]);
   }
  }  //end
}
```

Static

Output : Number of Iterations=4, CHUNKSIZE = 1, Number of Threads=4

Static

Output : Number of Iterations=4, CHUNKSIZE = 1, Number of Threads=4

```
[om@shrestha1 SampleCodes]$ gcc -fopenmp work_share1.c
[om@shrestha1 SampleCodes]$ ./a.out
Thread 1 starting...
Thread 1: c[1]= 2.000000
Thread 3 starting...
Thread 3: c[3]= 6.000000
Thread 2 starting...
Thread 2: c[2]= 4.000000
Number of threads = 4
Thread 0 starting...
Thread 0: c[0]= 0.000000
[om@shrestha1 SampleCodes]$
```

Static

Output : Number of Iterations=4, CHUNKSIZE = 1, Number of Threads=4

```
[om@shrestha1 SampleCodes]$ gcc -fopenmp work_share1.c
[om@shrestha1 SampleCodes]$ ./a.out
Thread 1 starting...
Thread 1: c[1]= 2.000000
Thread 3 starting...
Thread 3: c[3]= 6.000000
Thread 2 starting...
Thread 2: c[2]= 4.000000
Number of threads = 4
Thread 0 starting...
Thread 0: c[0]= 0.000000
[om@shrestha1 SampleCodes]$
```

Output : Number of Iterations=4, **CHUNKSIZE = 2**, Number of Threads=4

Static

Output : Number of Iterations=4, CHUNKSIZE = 1, Number of Threads=4

```
[om@shrestha1 SampleCodes]$ gcc -fopenmp work_share1.c
[om@shrestha1 SampleCodes]$ ./a.out
Thread 1 starting...
Thread 1: c[1]= 2.000000
Thread 3 starting...
Thread 3: c[3]= 6.000000
Thread 2 starting...
Thread 2: c[2]= 4.000000
Number of threads = 4
Thread 0 starting...
Thread 0: c[0]= 0.000000
[om@shrestha1 SampleCodes]$
```

Output : Number of Iterations=4, CHUNKSIZE = 2, Number of Threads=4

```
[om@shrestha1 SampleCodes]$ gcc -fopenmp work_share1.c
[om@shrestha1 SampleCodes]$ ./a.out
Thread 2 starting...
Thread 3 starting...
Number of threads = 4
Thread 0 starting...
Thread 0: c[0]= 0.000000
Thread 0: c[1]= 2.000000
Thread 1 starting...
Thread 1: c[2]= 4.000000
Thread 1: c[3]= 6.000000
[om@shrestha1 SampleCodes]$
```

Static

Output : Number of Iterations=4, **CHUNKSIZE = 4**, Number of Threads=4

Static

Output : Number of Iterations=4, CHUNKSIZE = 4, Number of Threads=4

```
[om@shrestha1 SampleCodes]$ gcc -fopenmp work_share1.c
[om@shrestha1 SampleCodes]$ ./a.out
Thread 1 starting...
Thread 3 starting...
Number of threads = 4
Thread 0 starting...
Thread 0: c[0]= 0.000000
Thread 0: c[1]= 2.000000
Thread 0: c[2]= 4.000000
Thread 0: c[3]= 6.000000
Thread 2 starting...
[om@shrestha1 SampleCodes]$
```

Static

Output : Number of Iterations=4, CHUNKSIZE = 4, Number of Threads=4

```
[om@shrestha1 SampleCodes]$ gcc -fopenmp work_share1.c
[om@shrestha1 SampleCodes]$ ./a.out
Thread 1 starting...
Thread 3 starting...
Number of threads = 4
Thread 0 starting...
Thread 0: c[0]= 0.000000
Thread 0: c[1]= 2.000000
Thread 0: c[2]= 4.000000
Thread 0: c[3]= 6.000000
Thread 2 starting...
[om@shrestha1 SampleCodes]$
```

Output : Number of Iterations=8, CHUNKSIZE = 2, Number of Threads=4

Static

Output : Number of Iterations=4, CHUNKSIZE = 4, Number of Threads=4

```
[om@shrestha1 SampleCodes]$ gcc -fopenmp work_share1.c
[om@shrestha1 SampleCodes]$ ./a.out
Thread 1 starting...
Thread 3 starting...
Number of threads = 4
Thread 0 starting...
Thread 0: c[0]= 0.000000
Thread 0: c[1]= 2.000000
Thread 0: c[2]= 4.000000
Thread 0: c[3]= 6.000000
Thread 2 starting...
[om@shrestha1 SampleCodes]$
```

Output : Number of Iterations=8, CHUNKSIZE = 2, Number of Threads=4

```
[om@shrestha1 SampleCodes]$ gcc -fopenmp work_share1.c
[om@shrestha1 SampleCodes]$ ./a.out
Thread 1 starting...
Thread 1: c[2]= 4.000000
Thread 1: c[3]= 6.000000
Thread 2 starting...
Thread 2: c[4]= 8.000000
Thread 2: c[5]= 10.000000
Thread 3 starting...
Thread 3: c[6]= 12.000000
Thread 3: c[7]= 14.000000
Number of threads = 4
Thread 0 starting...
Thread 0: c[0]= 0.000000
Thread 0: c[1]= 2.000000
[om@shrestha1 SampleCodes]$
```

Work Sharing : Scheduling

2. Dynamic

- Distribution is done during execution of the loop
  - Each thread is assigned a subset of the iterations at loop entry
  - After completion each thread asks for more iterations
- More flexible - Can easily adjust to load imbalances. Workload might randomly differ from iteration to iteration
- More scheduling overhead (synchronization)
- Threads request new chunks dynamically
- Default chunk size is 1

Example - 5 : Dynamic

Write a Parallel C program where the iterations of a loop should scheduled dynamically across the team of threads. A thread should perform CHUNK iterations at a time before being scheduled for the next CHUNK of work.

Dynamic

```
#include <omp.h>
#include <stdio.h>
#include <stdlib.h>
#define CHUNKSIZE   1
#define N  4

int main (int argc, char *argv[])
{
int nthreads, tid, i, chunk;
float a[N], b[N], c[N];

/* Some initializations */
for (i=0; i < N; i++)
  a[i] = b[i] = i * 1.0;
chunk = CHUNKSIZE;
```

```
#pragma omp parallel private(i,tid) //start
  {
  tid = omp_get_thread_num();
  if (tid == 0)
    {
    nthreads = omp_get_num_threads();
    printf("Number of threads = %d\n",
nthreads);
    }

  printf("Thread %d starting...\n",tid);
  #pragma omp for schedule(dynamic,chunk)
  for (i=0; i<N; i++)
   {
   c[i] = a[i] + b[i];
   printf("Thread %d: c[%d]=%f\n",tid,i,c[i]);
   }
  }  //end
}
```

Dynamic

Output : Number of Iterations=4, CHUNKSIZE = 1, Number of Threads=4

```
[om@shrestha1 SampleCodes]$ gcc -fopenmp work_share1.c
[om@shrestha1 SampleCodes]$ ./a.out
Number of threads = 4
Thread 0 starting...
Thread 3 starting...
Thread 3: c[1]= 2.000000
Thread 1 starting...
Thread 1: c[3]= 6.000000
Thread 2 starting...
Thread 3: c[2]= 4.000000
Thread 0: c[0]= 0.000000
[om@shrestha1 SampleCodes]$
```

… try to understand the difference !

<u>Note :</u> the default scheduling when no schedule clause is present is static with chunk size equal to #iterations / #threads

Work Sharing : Scheduling

3. guided

- First chunk has implementation-dependent size
- Size of each successive chunk decreases exponentially
- Chunks are assigned dynamically
- Chunks size specifies minimum size, default is 1
- Execution speed might increase/decrease with increasing iteration index
  - Chunksize is proportional to number of iterations left divided by the number of threads in the team

4. runtime

- Scheduling strategy is determined by environment variable at runtime
  - export OMP_SCHEDULE=type [, chunk]

Work Sharing : Sections

- A parallel section contains blocks of statements which can be executed in parallel
- Each block is executed once by one thread of the current team
- Scheduling of the block executions is implementation defined and cannot be controlled by the programmer
- Sections must not depend on each other
- Most frequent use case: parallel function calls

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

Example - 6 : Sections

```
#include <stdio.h>
#include <omp.h>
int main()
{
    unsigned char a = 5, b = 9, c=4, d=7, e=14, f=15;
    omp_set_num_threads(3);
    #pragma omp parallel sections
        {
          #pragma omp section {
              printf("Thread= %d, a^b = %d, \n",omp_get_thread_num(), a^b);
          }
          #pragma omp section {
              printf("Thread= %d, c^d = %d, \n",omp_get_thread_num(), c^d);
          }
          #pragma omp section {
              printf("Thread= %d, e^f = %d, \n",omp_get_thread_num(), e^f);
          }
        }
    return 0;
}
```

Output

```
[om@shrestha1 SampleCodes]$ gcc -fopenmp xor1.c
[om@shrestha1 SampleCodes]$ ./a.out
Thread= 0, a^b = 12,
Thread= 1, c^d = 3,
Thread= 2, e^f = 1,
[om@shrestha1 SampleCodes]$
```

Example - 7 : Section

Write a Parallel C program which should print the series of 2 and 4. Make sure both should be executed by different threads !

Example - 7 : Section

```
#include <stdio.h>
#include <omp.h>
#define N 10
int main() {
int i, a[N], b[N];
#pragma omp parallel sections private(i)
{
#pragma omp section
{
for (i=1 ; i<=N ; i++){
        a[i] = i*2;
        printf("Thread %d : %d \n",omp_get_thread_num(), a[i]);
        }
}
#pragma omp section
{
for (i=1 ; i<=N ; i++) {
        b[i] = i*4;
        printf("Thread %d : %d \n",omp_get_thread_num(), b[i]);
        }
}
}
}
```

Output

```
[om@shrestha1 SampleCodes]$ gcc -fopenmp section.c
[om@shrestha1 SampleCodes]$ ./a.out
Thread 0 : 2
Thread 0 : 4
Thread 0 : 6
Thread 0 : 8
Thread 0 : 10
Thread 0 : 12
Thread 0 : 14
Thread 0 : 16
Thread 0 : 18
Thread 0 : 20
Thread 1 : 4
Thread 1 : 8
Thread 1 : 12
Thread 1 : 16
Thread 1 : 20
Thread 1 : 24
Thread 1 : 28
Thread 1 : 32
Thread 1 : 36
Thread 1 : 40
[om@shrestha1 SampleCodes]$
```

Synchronization

To get accurate and proper results, synchronization among team members is must while working in team.

Race condition

<u>Race Condition :</u> When more than one thread try to update the shared data variable !

Race condition

<u>Race Condition :</u> When more than one thread try to update the shared data variable !

```c
#include<stdio.h>
#include <omp.h>
#define N 10

int main() {
double s = 0.0, a[N];
int i;
// initialize the array
for (i=0; i < N; i++){
  a[i] = i * 1.0;
}
#pragma omp parallel for
{
     for (i=0 ; i<N ; ++i)
     {
     s += a[i];
     }
}
printf("s = %f \n", s);
}
```

What is Expected Output of this Program ?

Race condition

Race Condition : When more than one thread try to update the shared data variable !

```
#include<stdio.h>
#include <omp.h>
#define N 10

int main() {
double s = 0.0, a[N];
int i;
// initialize the array
for (i=0; i < N; i++){
  a[i] = i * 1.0;
}
#pragma omp parallel for
{
     for (i=0 ; i<N ; ++i)
     {
     s += a[i];
     }
}
printf("s = %f \n", s);
}
```

What is Expected Output of this Program ?

Print sum of 0 - 9 numbers !

Race condition

Race Condition : When more than one thread try to update the shared data variable !

```
#include<stdio.h>
#include <omp.h>
#define N 10

int main() {
double s = 0.0, a[N];
int i;
// initialize the array
for (i=0; i <N; i++){
  a[i] = i * 1.0;
}
#pragma omp parallel for
{
     for (i=0 ; i<N ; ++i)
     {
     s += a[i];
     }
}
printf("s = %f \n", s);
}
```

Expected Output : s = 45

Race condition

Race Condition : When more than one thread try to update the shared data variable !

```c
#include<stdio.h>
#include <omp.h>
#define N 10

int main() {
double s = 0.0, a[N];
int i;
// initialize the array
for (i=0; i <N; i++){
  a[i] = i * 1.0;
}
#pragma omp parallel for
{
     for (i=0 ; i<N ; ++i)
     {
     s += a[i];
     }
}
printf("s = %f \n", s);
}
```

Expected Output : s = 45

```
[om@shrestha1 SampleCodes]$ gcc -fopenmp race.c
[om@shrestha1 SampleCodes]$ ./a.out
s = 29.000000
[om@shrestha1 SampleCodes]$ ./a.out
s = 21.000000
[om@shrestha1 SampleCodes]$ ./a.out
s = 45.000000
[om@shrestha1 SampleCodes]$ ./a.out
s = 45.000000
[om@shrestha1 SampleCodes]$ ./a.out
s = 45.000000
[om@shrestha1 SampleCodes]$ ./a.out
s = 45.000000
[om@shrestha1 SampleCodes]$ ./a.out
s = 43.000000
[om@shrestha1 SampleCodes]$
```

Race condition

<u>Race Condition :</u> When more than one thread try to update the shared data variable !

```
#include<stdio.h>
#include <omp.h>
#define N 10

int main() {
double s = 0.0, a[N];
int i;
// initialize the array
for (i=0; i <N; i++){
  a[i] = i * 1.0;
}
#pragma omp parallel for
{
     for (i=0 ; i<N ; ++i) {
     {
     s += a[i];
     }
}
printf("s = %f \n", s);
}
```

Expected Output : s = 45

Solution ?

Synchronization : critical

- A critical region restricts execution of the associated block of statements to a single thread at a time

- A thread waits at the beginning of a critical region until no other thread is executing a critical region (anywhere in the program) with the same name

- Mutual exclusion : Only one thread at a time can enter the critical region.

Synchronization : critical

```c
#include<stdio.h>
#include <omp.h>
#define N 10

int main() {
double s = 0.0, a[N];
int i;
// initialize the array
for (i=0; i < N; i++){
  a[i] = i * 1.0;
}
#pragma omp parallel for
{
     for (i=0 ; i<N ; ++i)
     {
     s += a[i];
     }
}
printf("s = %f \n", s);
}
```

Expected Output : s = 45

Synchronization : critical

```
#include<stdio.h>
#include <omp.h>
#define N 10

int main() {
double s = 0.0, a[N];
int i;
// initialize the array
for (i=0; i < N; i++){
  a[i] = i * 1.0;
}
#pragma omp parallel for
{
     for (i=0 ; i<N ; ++i)
     {
     #pragma omp critical
     s += a[i];
     }
}
printf("s = %f \n", s);
}
```

Expected Output : s = 45

Synchronization : critical

```c
#include<stdio.h>
#include <omp.h>
#define N 10

int main() {
double s = 0.0, a[N];
int i;
// initialize the array
for (i=0; i < N; i++){
  a[i] = i * 1.0;
}
#pragma omp parallel for
{
     for (i=0 ; i<N ; ++i)
     {
     #pragma omp critical
     s += a[i];
     }
}
printf("s = %f \n", s);
}
```

Expected Output : s = 45

```
[om@shrestha1 SampleCodes]$ gcc -fopenmp cri.c
[om@shrestha1 SampleCodes]$ ./a.out
s = 45.000000
[om@shrestha1 SampleCodes]$ ./a.out
s = 45.000000
[om@shrestha1 SampleCodes]$ ./a.out
s = 45.000000
[om@shrestha1 SampleCodes]$ ./a.out
s = 45.000000
[om@shrestha1 SampleCodes]$
```

Synchronization : critical

```
#include<stdio.h>
#include <omp.h>
#define N 10

int main() {
double s = 0.0, a[N];
int i;
// initialize the array
for (i=0; i < N; i++){
  a[i] = i * 1.0;
}
#pragma omp parallel for
{
     for (i=0 ; i<N ; ++i)
     {
     #pragma omp critical
     s += a[i];
     }
}
printf("s = %f \n", s);
}
```

Expected Output : s = 45

... but, wait and Think !

Synchronization : critical

```
#include<stdio.h>
#include <omp.h>
#define N 10

int main() {
double s = 0.0, a[N];
int i;
// initialize the array
for (i=0; i < N; i++){
  a[i] = i * 1.0;
}
#pragma omp parallel for
{
     for (i=0 ; i<N ; ++i)
     {
     #pragma omp critical
     s += a[i];
     }
}
printf("s = %f \n", s);
}
```

Expected Output : s = 45

... but, wait and Think !

Code is getting executed almost Serially !

Synchronization : critical

```
#include<stdio.h>
#include <omp.h>
#define N 10

int main() {
double s = 0.0, a[N];
int i;
// initialize the array
for (i=0; i < N; i++){
  a[i] = i * 1.0;
}
#pragma omp parallel for
{
     for (i=0 ; i<N ; ++i)
     {
     #pragma omp critical
     s += a[i];
     }
}
printf("s = %f \n", s);
}
```

Expected Output : s = 45

Always use critical (& other synchronization !) regions with precautions.

Program gets extremely slow : No speedup

Synchronization : critical

```
#include<stdio.h>
#include <omp.h>
#define N 10

int main() {
double s = 0.0, a[N];
int i;
// initialize the array
for (i=0; i < N; i++){
  a[i] = i * 1.0;
}
#pragma omp parallel for
{
     for (i=0 ; i<N ; ++i)
     {
     #pragma omp critical
     s += a[i];
     }
}
printf("s = %f \n", s);
}
```

Expected Output : s = 45

Any better Solution ?

Synchronization : critical

```
#include<stdio.h>
#include <omp.h>
#define N 10

int main() {
double s = 0.0, a[N],  s_local;
int i;
// initialize the array
for (i=0; i < N; i++){
  a[i] = i * 1.0;
}
#pragma omp parallel private(i, s_local)
{
      #pragma omp for
      for (i=0 ; i<N ; ++i)
      {
      s_local += a[i];
      }
      #pragma omp critical
      {
      s += s_local;
      }
}
printf("s = %f \n", s);
}
```

Expected Output : s = 45

Critical section has moved outside of the loop

Synchronization : critical

```c
#include<stdio.h>
#include <omp.h>
#define N 10

int main() {
double s = 0.0, a[N], s_local;
int i;
// initialize the array
for (i=0; i < N; i++){
  a[i] = i * 1.0;
}
#pragma omp parallel private(i, s_local)
{
      #pragma omp for
      for (i=0 ; i<N ; ++i)
      {
      s_local += a[i];
      }
      #pragma omp critical
      {
      s += s_local;
      }
}
printf("s = %f \n", s);
}
```

Expected Output : s = 45

```
[om@shrestha1 SampleCodes]$ gcc -fopenmp cri1.c
[om@shrestha1 SampleCodes]$ ./a.out
s = 45.000000
[om@shrestha1 SampleCodes]$ ./a.out
s = 45.000000
[om@shrestha1 SampleCodes]$ ./a.out
s = 45.000000
[om@shrestha1 SampleCodes]$ ./a.out
s = 45.000000
[om@shrestha1 SampleCodes]$
```

Synchronization : critical

Performance Comparison : N = 1000000

Synchronization : critical

Performance Comparison : N = 1000000

```
[om@shrestha1 SampleCodes]$ gcc -fopenmp cri.c
[om@shrestha1 SampleCodes]$ time ./a.out
s = 499999500000.000000

real    0m3.508s
user    0m17.826s
sys     0m0.009s
[om@shrestha1 SampleCodes]$
```

```
[om@shrestha1 SampleCodes]$ export OMP_NUM_THREADS=8
[om@shrestha1 SampleCodes]$ gcc -fopenmp cri1.c
[om@shrestha1 SampleCodes]$ time ./a.out
s = 499999500000.000000

real    0m0.009s
user    0m0.001s
sys     0m0.013s
[om@shrestha1 SampleCodes]$
```

Synchronization : Atomic

```
#include<stdio.h>
#include <omp.h>
#define N 10

int main() {
double s = 0.0, a[N],  s_local;
int i;
// initialize the array
for (i=0; i < N; i++){
  a[i] = i * 1.0;
}
#pragma omp parallel private(i, s_local)
{
      #pragma omp for
      for (i=0 ; i<N ; ++i)
      {
      s += a[i];
      }
      #pragma omp critical
      {
      s += s_local;
      }
}
printf("s = %f \n", s);
}
```

Any other solution ?

Synchronization : Atomic

```
#include<stdio.h>
#include <omp.h>
#define N 10

int main() {
double s = 0.0, a[N],  s_local;
int i;
// initialize the array
for (i=0; i < N; i++){
  a[i] = i * 1.0;
}
#pragma omp parallel private(i, s_local)
{
      #pragma omp for
      for (i=0 ; i<N ; ++i)
      {
      s += a[i];
      }
      #pragma omp critical
      {
      s += s_local;
      }
}
printf("s = %f \n", s);
}
```

Any other solution ?

Synchronization : Atomic

```
#include<stdio.h>
#include <omp.h>
#define N 10

int main() {
double s = 0.0, a[N], s_local;
int i;
// initialize the array
for (i=0; i < N; i++){
  a[i] = i * 1.0;
}
#pragma omp parallel private(i, s_local)
{
      #pragma omp for
      for (i=0 ; i<N ; ++i)
      {
      s += a[i];
      }
      #pragma omp atomic
      s += s_local;
}
printf("s = %f \n", s);
}
```

- The ATOMIC directives ensures that a specific memory location is updated atomically. No thread interference
- Only a single variable/line gets affected and not the block.
- ATOMIC construct permits better optimization (based on hardware instructions)

Synchronization : Atomic

```c
#include<stdio.h>
#include <omp.h>
#define N 10

int main() {
double s = 0.0, a[N],  s_local;
int i;
// initialize the array
for (i=0; i < N; i++){
  a[i] = i * 1.0;
}
#pragma omp parallel private(i, s_local)
{
      #pragma omp for
      for (i=0 ; i<N ; ++i)
      {
      s += a[i];
      }
      #pragma omp atomic
      s += s_local;
}
printf("s = %f \n", s);
}
```

Expected Output : s = 45

```
[om@shrestha1 SampleCodes]$ gcc -fopenmp atomic.c
[om@shrestha1 SampleCodes]$ ./a.out
s = 45.000000
[om@shrestha1 SampleCodes]$ ./a.out
s = 45.000000
[om@shrestha1 SampleCodes]$ ./a.out
s = 45.000000
[om@shrestha1 SampleCodes]$ ./a.out
s = 45.000000
[om@shrestha1 SampleCodes]$
```

More about synchronization

Sometimes it is useful that within a parallel region just one thread is executing code, e.g., to read/write data. OpenMP provides two ways to accomplish this

- **Master construct :**
  - The master thread (thread 0) executes the enclosed code, all other threads ignore this block of statements, i.e. there is no implicit barrier

```
#pragma omp master
    structured block
```

- **Single construct :**
  - The first thread reaching the directive executes the code. All threads execute an implicit barrier

```
#pragma omp single [nowait, private(list),...]
structured block
```

More about synchronization

- **<u>Barrier :</u>**
  - The barrier directive explicitly synchronizes all the threads in a team.
  - When encountered, each thread in the team waits until all the others have reached this point
  - There are also implicit barriers at the end of parallel region, cannot be changed of work share constructs e.g SECTIONS.

```
#pragma omp barrier
```

```
#include<stdio.h>
#include <omp.h>
#define N 10

int main() {
double s = 0.0, a[N],  s_local;
int i;
// initialize the array
for (i=0; i < N; i++){
  a[i] = i * 1.0;
}
#pragma omp parallel private(i, s_local)
{
      #pragma omp for
      for (i=0 ; i<N ; ++i)
      {
      s_local += a[i];
      }
      #pragma omp atomic
      s += s_local;
}
printf("s = %f \n", s);
}
```

Expected Output : s = 45

Any other better better way to perform such operations ?

Reduction

- Reductions often occur within parallel regions or loops
- Reduction variables have to be shared in enclosing parallel context
- Thread-local results get combined with outside variables using reduction operation
- Typical applications: Compute sum of array or find the largest element

```
reduction(operator | intrinsic : varlist )
```

- **<u>Note:</u>** order of operations unspecified → can produce slightly different results than sequential version (rounding error)

Reduction

```
#include<stdio.h>
#include <omp.h>
#define N 10

int main() {
double s = 0.0, a[N], s_local;
int i;
// initialize the array
for (i=0; i < N; i++){
  a[i] = i * 1.0;
}
#pragma omp parallel private(i, s_local)
{
      #pragma omp for
      for (i=0 ; i<N ; ++i)
      {
      s += a[i];
      }
      #pragma omp atomic
      s += s_local;
}
printf("s = %f \n", s);
}
```

Expected Output : s = 45

Reduction

```
#include<stdio.h>
#include <omp.h>
#define N 10

int main() {
double s = 0.0, a[N] ;
int i;
// initialize the array
for (i=0; i < N; i++){
  a[i] = i * 1.0;
}
#pragma omp parallel for private(i) reduction(+:s)
{
      for (i=0 ; i<N ; ++i)
      {
      s += a[i];
      }
}
printf("s = %f \n", s);
}
```

Expected Output : s = 45

Reduction

```c
#include<stdio.h>
#include <omp.h>
#define N 10

int main() {
double s = 0.0, a[N];
int i;
// initialize the array
for (i=0; i < N; i++){
  a[i] = i * 1.0;
}
#pragma omp parallel for private(i) reduction(+:s)
{
      for (i=0 ; i<N ; ++i)
      {
      s += a[i];
      }
}
printf("s = %f \n", s);
}
```

Expected Output : s = 45

```
[om@shrestha1 SampleCodes]$ gcc -fopenmp reduction.c
[om@shrestha1 SampleCodes]$ ./a.out
s = 45.000000
[om@shrestha1 SampleCodes]$ ./a.out
s = 45.000000
[om@shrestha1 SampleCodes]$ ./a.out
s = 45.000000
[om@shrestha1 SampleCodes]$
```

Reduction

Operator	Data Type	Initial Value
+	Floating point, Integer	0
*	Floating point, Integer	1
-	Floating point, Integer	0
&	Integer	all bits on
|	Integer	0
^	Integer	0
&&	Integer	1
||	Integer	0

- The table shows: The operators and intrinsic allowed for reductions The initial values used to initialize
- Since OpenMP 3.1: min, max

Career Opportunities in HPC

- **HPC System Administrator:** Installation, configuration, and maintenance of HPC systems
- **HPC Application Developer:** Develop software applications that can take advantage of the high-performance computing resources available
- **HPC Performance Engineer:** Analyzing and optimizing the performance of HPC systems and applications
- **HPC Data Scientist:** Analyze large and complex datasets
- **HPC Researcher:** research in various areas related to HPC, such as algorithm development, performance optimization, or system architecture
- **HPC Education and Training:** develop and deliver training programs and courses on HPC technology and applications
- **HPC Consultant:** promote and sell HPC systems and solutions to potential customers etc

Any questions ?