Introduction to Parallel Programming using OpenMP

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Outline

Download the support material

- **Use ssh client:** PuTTy, MobaXterm, Terminal (Mac or Linux) to connect to cedar and/or graham:
  - ssh –Y username@cedar.computecanada.ca
  - ssh –Y username@graham.computecanada.ca

- Download the files using wget:

```
wget https://ali-kerrache.000webhostapp.com/uofm/openmp.tar.gz
wget https://ali-kerrache.000webhostapp.com/uofm/openmp-slides.pdf
```

- Unpack the archive and change the directory:

```
tar -xvf openmp.tar.gz
cd UofM-Summer-School-OpenMP
```

Concurrency and parallelism

Concurrency:

- Condition of a system in which multiple tasks are logically active at the same time … but they may not necessarily run in parallel.

Parallelism:

- subset of concurrency

- Condition of a system in which multiple tasks are active at the same time and run in parallel.

What do we mean by parallel machines?

Introduction of parallel programming

Serial Programming:

- Develop a serial program.
- Performance & Optimization?

But in real world:

- Run multiple programs.
- Large & complex problems.
- Time consuming.

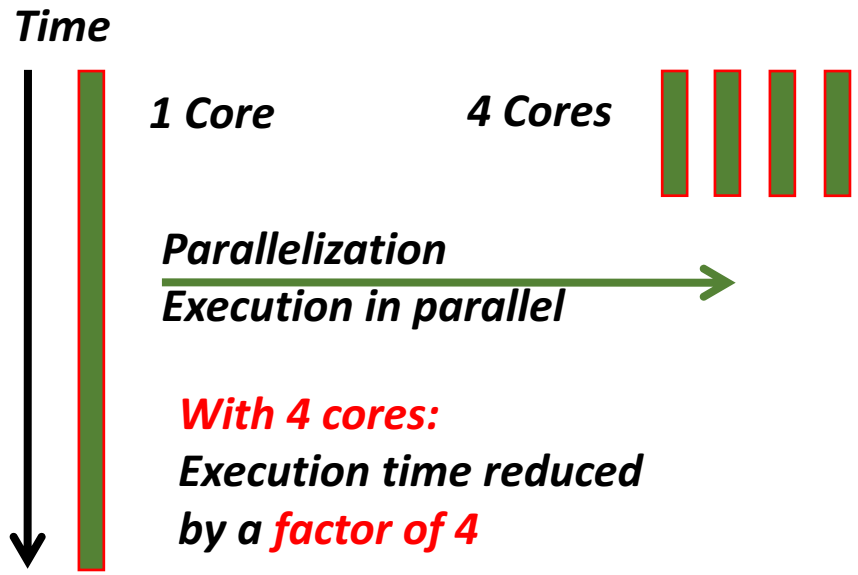
Solution:

- Use Parallel Machines.
- Use Multi-Core Machines.

Why Parallel?

- Reduce the execution time.
- Run multiple programs.

Example:

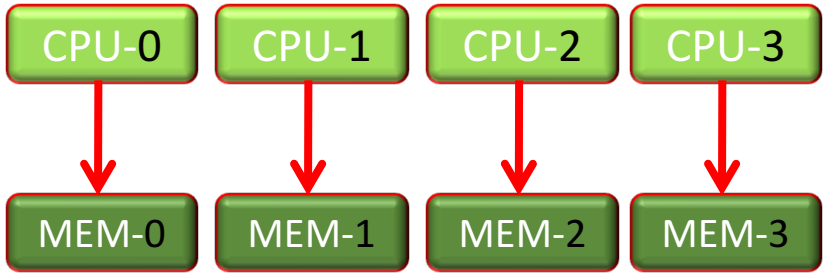


What is Parallel Programming?

Obtain the same amount of computation with multiple cores at low frequency (fast).

Parallel machines & parallel programming

Distributed Memory Machines



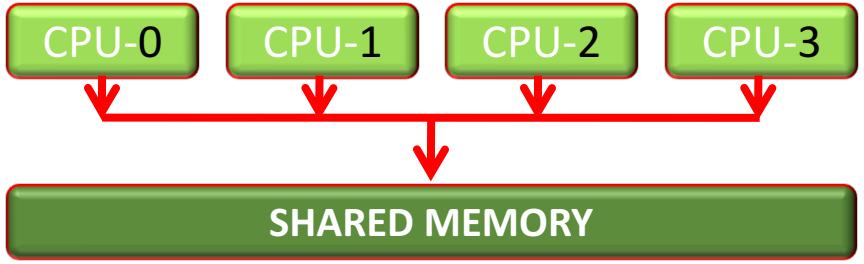
- Each processor has its **own memory**.
- The variables are **independent**.
- Communication by **passing messages** (network).

Multi-Processing

- **Difficult** to program.
- **Scalable**.

MPI based programming

Shared Memory Machines



- All processors **share** the **same memory**.
- The variables can be **shared** or **private**.
- Communication via **shared memory**.

Multi-Threading

- Portable, **easy** to program and use.
- **Not very scalable**.

OpenMP based programming

Definition of OpenMP: API

- **Library** used to **divide** computational **work** in a program and add **parallelism** to a serial program (**create threads**).
- **Supported** by compilers: **Intel** (ifort, icc), **GNU** (gcc, gfortran, …).
- Programming languages: C/C++, Fortran.

- **Compilers:** http://www.openmp.org/resources/openmp-compilers/

OpenMP

Compiler Directives	Runtime Library	Environment Variables
Directives to add to a serial program. Interpreted at compile time.	Directives executed at run time.	Directives introduced after compile time to control & execute OpenMP program.

Construction of an OpenMP program

Application / Serial program / End user

OpenMP

Compiler Directives | Runtime Library | Environment Variables

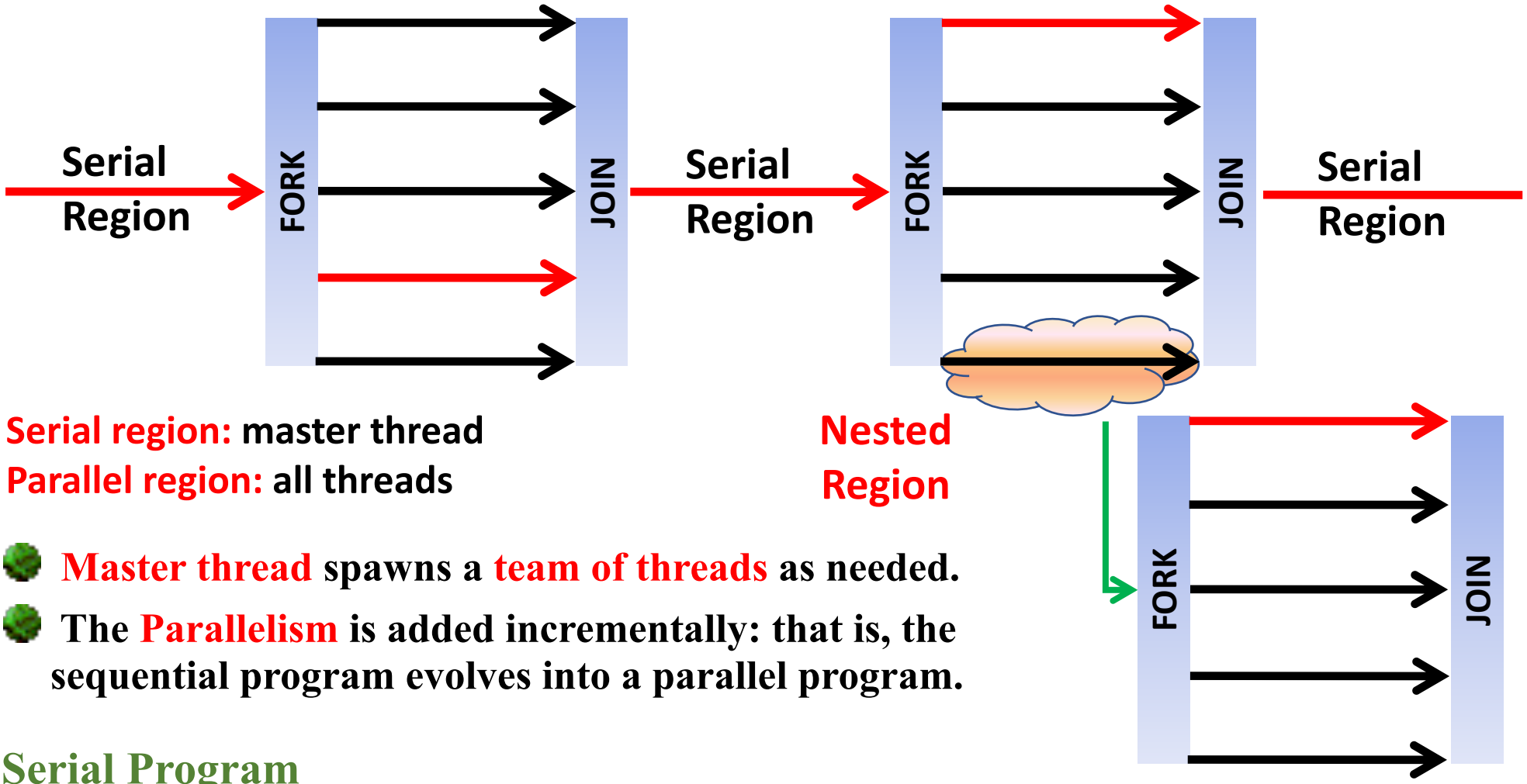
Compilation / Runtime Library / Operating System

Thread creation & Parallel Execution

Thread 0 | Thread 1 | Thread 2 | Thread 3 | Thread 4 | ... | N-1

What is the OpenMP programming model?

OpenMP model: Fork-Join parallelism



Serial region: master thread
Parallel region: all threads

- **Master thread** spawns a **team of threads** as needed.
- The **Parallelism** is added incrementally: that is, the sequential program evolves into a parallel program.

Serial Program

Define the regions to **parallelize**, then **add OpenMP** directives

Learn OpenMP by examples

- **Example_00: Threads creation.**
  - ✓ How to go from a serial code to a parallel code?
  - ✓ How to **create threads**?
  - ✓ Introduce some **constructs** of OpenMP.
  - ✓ Compile and run an OpenMP program
- **Example_01: Work sharing** using:
  - ✓ **Loops**
  - ✓ **Sections**
- **Example_02: Common problem in OpenMP programming.**
  - ✓ False sharing and race conditions.
- **Example_03: Single Program Multiple Data model:**
  - ✓ as solution to **avoid race conditions**.
- **Example_04:**
  - ✓ **More** OpenMP **constructs.**
  - ✓ **Synchronization**.

OpenMP: simple syntax

Most of the constructs in **OpenMP** are compiler directives or **pragma**:

- For C/C++, the **pragma** take the form:

  #pragma omp *construct* *[clause [clause]…]*

- For Fortran, the directives take one of the forms:

  !$OMP *construct* *[clause [clause]…]*
  C$OMP *construct* *[clause [clause]…]*
  $OMP *construct* *[clause [clause]…]

```
#include <omp.h>
#pragma omp parallel
{
Block of a C/C++ code;
}
```

```
use omp_lib
!$omp parallel
Block of Fortran code
!$omp end parallel
```

- ✓ *For **C/C++** include the **H**eader* file: **#include <omp.h>**
- ✓ *For* **Fortran 90** use the **module**: **use omp_lib**
- ✓ For **F77** include the Header file: **include 'omp_lib.h'**

Parallel regions & structured blocks

Most of **OpenMP** constructs apply to **structured blocks**

- **Structured block:** a block with one point of entry at the top and one point of exit at the bottom.
- The only "**branches**" allowed are **STOP** statements in Fortran and **exit()** in C/C++

Structured block

```
#pragma omp parallel
{
int id = omp_get_thread_num();

more: res[id] = do_big_job (id);

if  (conv (res[id]) goto more;
}
printf ("All done\n");
```

Non structured block

```
if  (go_now()) goto more;
#pragma omp parallel
{
int id = omp_get_thread_num();
more:  res[id] = do_big_job(id);
if  (conv (res[id]) goto done;
goto more;
}
done: if  (!Really_done()) goto more;
```

Compile and run OpenMP program

- **Compile and enable OpenMP library:**
  - **GNU:** add **–fopenmp** to C/C++ & Fortran compilers.
  - **Intel compilers:** add **–openmp** (accept also **–fopenmp**)
  - ✓ ***PGI Linux compilers:*** add **–mp**
  - ✓ ***Windows:*** add **/Qopenmp**

- **Set the environment variable: OMP_NUM_THREADS**
  - ✓ **OpenMP** will spawns **one thread** per **hardware thread**.
  - **$ export OMP_NUM_THREADS=value** (*bash shell*)
  - ***$ setenv OMP_NUM_THREADS value*** (*tcsh shell*)

    value: number of threads [For example 4]

- **Execute or run the program:**
  - **$ ./exec_program {options, parameters}** or **./a.out**

Submission script: SLURM

```
#!/bin/bash
#SBATCH --nodes=1
#SBATCH --ntasks=1
#SBATCH --cpus-per-task=4
#SBATCH --mem-per-cpu=2500M
#SBATCH --time=0-00:30

# Load compiler module and/or your
# application module.

cd $SLURM_SUBMIT_DIR
export OMP_NUM_THREADS=$SLURM_CPUS_PER_TASK

echo "Starting run at: `date`"

./your_openmp_program_exec {options and/or parameters}

echo "Program finished with exit code $? at: `date`"
```

Resources:

- nodes=1
- ntasks=1
- cpus-per-task=1 to number of cores

- Cedar: nodes with 32 or 48 cores
- Graham: nodes with 32 cores
- Niagara: nodes with 40 cores

Submission script: PBS

```
#!/bin/bash
#PBS -S /bin/bash
#PBS –l nodes=1:ppn=4
#PBS –l pmem=2000mb
#PBS –l walltime=24:00:00
#PBS –M <your-valid-email>
#PBS –m abe

# Load compiler module
# and/or your application
# module.

cd $PBS_O_WORKDIR
echo "Current working directory is `pwd`"
export OMP_NUM_THREADS=$PBS_NUM_PPN
./your_openmp_exec < input_file > output_file
echo "Program finished at: `date`"
```

Resources:

- ✓ nodes=1
- ✓ ppn=1 to maximum of N CPU (hardware)
- ✓ nodes=1:ppn=4 (for example).

```
# On systems where $PBS_NUM_PPN is not
available, one could use:
CORES=`/bin/awk 'END {print NR}'
$PBS_NODEFILE`

export OMP_NUM_THREADS=$CORES
```

Data environment

shared

- only a **single instance** of variables in shared memory.
- all threads have **read** and **write** access to these variables.

private

- Each **thread** allocates its **own private copy** of the data.
- These local copies **only exist** in **parallel** region.
- **Undefined** when **entering** or **exiting** the parallel region.

firstprivate

- variables are also declared to be **private**.
- additionally, get **initialized** with value of original variable.

lastprivate

- declares variables as **private**.
- variables get **value** from the **last iteration** of the loop.

C/C++: default (shared | none)
Fortran: default (private | firstprivate | shared | none)

It is highly recommended to use: default (none)

Hello World! program: serial version

❖**Objective:** simple serial program in **C/C++** and **Fortran**

❖ **Directory:** **Example_00** {hello_c_seq.c; hello_f90_seq.f90}

C/C++ program

```
#include <stdio.h>
int main() {
    printf("Hello World\n");
}
```

Fortran 90 program

```
program Hello
   implicit none
   write(*,*) "Hello World"
end program Hello
```

❖**To do:** compile and run the serial program (C/C++ or Fortran).

- **C/C++:**
  - **icc [CFLAGS]** hello_c_seq.c –o exec_prog.x
  - **gcc [CFLAGS]** hello_c_seq.c –o exec_prog.x
- **Fortran:**
  - **ifort [FFLAGS]** hello_f90_seq.f90 –o exec_prog.x
  - **gfortran [FFLAGS]** hello_f90_seq.f90 –o exec_prog.x
- **Run the program: ./a.out or ./exec_prog.x**

Hello World! program: parallel version

❖**Objective:** create a parallel region and spawns threads.
❖ **Directory:** Example_00
❖ **Templates:** hello_c_omp-template.c; hello_f90_omp-template.f90

For C/C++ program	For Fortran 90 program

`#include <omp.h>`
 	
`#pragma omp parallel`
	`use omp_lib`
	`!$omp parallel`
	`!$omp end parallel`

❖**To do:**

- Edit the program template and add OpenMP directives:
  - ✓ compiler directives.
- Compile and run the program of your choice (C/C++, Fortran).
  - ✓ Set the number of threads to 4 and run the program.

Hello World!

C/C++

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

Header

Compiler directives

Fortran 90

```
program Hello
   use omp_lib
   implicit none
!$omp parallel
   write(*,*) "Hello World"
!$omp end parallel

end program Hello
```

module

Compiler directives

- C and C++ use **exactly** the **same constructs**.
- **Slight differences** between C/C++ and Fortran.

Next example: ***helloworld_*_template.****

Runtime Library

Thread rank: ➢ **omp_get_thread_num();**
Number of threads: ➢ **omp_get_num_threads();**
Set number of threads: ➢ **omp_set_num_threads() ;**
Compute time: ➢ **omp_get_wtime() ;**

Overview of the program Hello World!

```
#include <omp.h>
#define NUM_THREADS 4
int main() {
  int ID, nthr, nthreads;  double start_time, elapsed_time;
  omp_set_num_threads(NUM_THREADS);
  nthr = omp_get_num_threads();
  start_time = omp_get_wtime();
  #pragma omp parallel default(none) private(ID) shared(nthreads)  {
    ID = omp_get_thread_num(); nthreads = omp_get_num_threads();
    printf("Hello World!; My ID is equal to [ %d ] – The total of threads is: [ %d ]\n",
    ID,  nthreads);   }
  elapsed_time = omp_get_wtime() - start_time;
  printf("\nThe time spend in the parallel region is: %f\n\n", elapsed_time);
  nthr = omp_get_num_threads();
  printf("Number of threads is: %d\n\n",nthr);
}
```

Development: set number of threads.
Production: use OMP_NUM_THREADS

Set OMP_NUM_THREADS
Get number of threads (Nth = 1)

Compute elapsed time.

Get OMP_NUM_THREADS
Print number of threads (Nth = 1)

Execution of the program Hello World!

Compile

```
$ icc –openmp helloworld_c_omp.c
$ gcc –fopenmp helloworld_c_omp.c
```

Compile

```
$ ifort –openmp helloworld_f90_omp.f90
$ gfortran –fopenmp helloworld_f90_omp.f90
```

Run the program for **OMP_NUM_THREADS** between 1 to 4

Execute the program

```
$  export OMP_NUM_THREADS=4
$ ./a.out
Hello World!; My ID is equal to [ 0 ] - The total of threads is: [ 4 ]
Hello World!; My ID is equal to [ 3 ] - The total of threads is: [ 4 ]
Hello World!; My ID is equal to [ 1 ] - The total of threads is: [ 4 ]
Hello World!; My ID is equal to [ 2 ] - The total of threads is: [ 4 ]
$ ./a.out
Hello World!; My ID is equal to [ 3 ] - The total of threads is: [ 4 ]
Hello World!; My ID is equal to [ 0 ] - The total of threads is: [ 4 ]
Hello World!; My ID is equal to [ 2 ] - The total of threads is: [ 4 ]
Hello World!; My ID is equal to [ 1 ] - The total of threads is: [ 4 ]
```

```
$  export OMP_NUM_THREADS=1
$ ./a.out
$  export OMP_NUM_THREADS=2
$ ./a.out
$  export OMP_NUM_THREADS=3
$ ./a.out
$  export OMP_NUM_THREADS=4
$ ./a.out
```

Work sharing: loops in OpenMP

OpenMP directives for loops:

- **C/C++**
  - **#pragma omp parallel for { ... }**
  - **#pragma omp for { … }**
- **Fortran**

```
!$OMP PARALLEL DO
...
!$OMP END PARALLEL DO

!$OMP DO
…
!OMP END DO
```

C/C++

```
#pragma omp parallel
{
   #pragma omp for
   {
   calc();
   }
}
#pragma omp parallel for { calc(); }
```

Fortran

```
!$omp parallel
!$omp do
!$omp end do
!$omp end parallel
!$omp parallel do
!$omp end parallel do
```

Work sharing: loops in OpenMP

C/C++

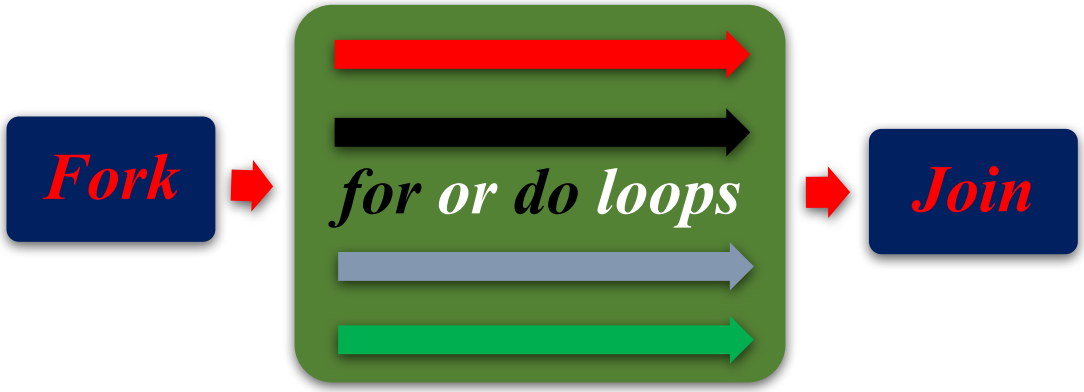
```
#pragma omp parallel
{
#pragma omp for

    for (i = 0; i < nloops; i++)
        do_some_computation();
}
```

#pragma omp parallel for { …. }

Fortran

```
!$omp parallel
!$omp do
    do i = 1, nloops
        do_some_computation
    end do
!$omp end do
!$omp end parallel
```

!$omp parallel do
!$omp end parallel do



Loops in OpenMP: Hello World!

C/C++

File: Example_01/

helloworld_loop_c_omp.cpp

```
#include <omp.h>
#define nloops 8
int main()
{
int ID, nthreads;
#pragma omp parallel default(none) private(ID) shared(nthreads) {
    ID = omp_get_thread_num();
    if ( ID == 0 ) { nthreads = omp_get_num_threads(); }
    int i;
    #pragma omp for
    for (i = 0; i < nloops; i++) {
        printf("Hello World!;
        My ID is equal to [ %d of %d ] –
        I get the value [ %d ]\n",ID,nthreads,i);   }
    }
}
```

```
#pragma omp single
    nthreads = omp_get_num_threads();
```

Directives on multiple lines

C/C++

```
#pragma omp parallel  list-of-some-directives \
            list-of-other-directives \
            list-of some-other-directives
{
structured block of C/C++ code;
}
```

The list of directives continues on the next lines

Fortran

```
!$omp parallel  list-of-some-directives &
!$omp  list-of-other-directives &
!$omp  list-of some-other-directives
structured block of Fortran code
!$omp end parallel
```

The list of directives continues on the next lines

Loops in OpenMP: Hello World!

Fortran

File: Example_01/

helloworld_loop_f90_omp.f90

```
use omp_lib
implicit none
integer :: ID, nthreads, i
integer, parameter :: nloops = 8

!$omp parallel default(none) shared (nthreads) private(ID)
    ID = omp_get_thread_num()
    if ( ID ==0 ) nthreads = omp_get_num_threads()

!$omp do
    do i = 0, nloops - 1
        write(*,fmt="(a,I2,a,I2,a,I2,a)") "Hello World!, My ID is equal to &
              & [ ", ID, " of ",nthreads, " ] - I get the value [ ",i, "]"
    end do
!$omp end do
!$omp end paralle
```

```
!$omp single
      nthreads = omp_get_num_threads()
!$omp end single
```

Conditional compilation

C/C++ and Fortran (last versions of OpenMP: 4.0)

Preprocessor macro **_OPENMP** for C/C++ and Fortran

```
#ifdef _OPENMP
MyID = omp_get_thread_num();
#endif
```

- Taken into account when compiled with OpenMP.
- Ignored if compiled in serial mode.

Special comment for Fortran preprocessor

```
!$ MyID = OMP_GET_THREAD_NUM()
```

Helpful check of serial and parallel version of the code

Loops in OpenMP: Hello World!

Compile and run the program

```
$ export OMP_NUM_THREADS=2
$ ./a.out
Hello World!; My ID is equal to [ 0 of 2 ] - I get the value [ 0 ]
Hello World!; My ID is equal to [ 1 of 2 ] - I get the value [ 4 ]
Hello World!; My ID is equal to [ 0 of 2 ] - I get the value [ 1 ]
Hello World!; My ID is equal to [ 1 of 2 ] - I get the value [ 5 ]
Hello World!; My ID is equal to [ 0 of 2 ] - I get the value [ 2 ]
Hello World!; My ID is equal to [ 1 of 2 ] - I get the value [ 6 ]
Hello World!; My ID is equal to [ 0 of 2 ] - I get the value [ 3 ]
Hello World!; My ID is equal to [ 1 of 2 ] - I get the value [ 7 ]
```

```
$ export OMP_NUM_THREADS=1
$ ./a.out
$ export OMP_NUM_THREADS=2
$ ./a.out
$ export OMP_NUM_THREADS=3
$ ./a.out
$ export OMP_NUM_THREADS=4
$ ./a.out
```

- Thread **0** gets the values: **0, 1, 2, 3**
- Thread **1** gets the values: **4, 5, 6, 7**

Example of output using: **8** loops and **2** threads

- Thread **0** gets the values: **0, 1, 2**
- Thread **1** gets the values: **3, 4, 5**
- Thread **2** gets the values: **6, 7**

Example of output using: **8** loops and **3** threads

What we have learned from "Hello World"?

- **Create threads:**
  - **C/C++: #pragma omp parallel { …….. }**
  - **Fortran: !$omp parallel ….. !$omp end parallel**
- Include the header: **<omp.h>** in **C/C++**; and **use omp_lib** in **Fortran**
- **Number of threads: omp_get_num_threads()**
- **Thread number or rank: omp_get_thread_num()**
- **Set number of threads: omp_set_num_threads()**
- **Evaluate the time: omp_get_wtime()**
- **single** construct: **omp_single()**
- **Variables:**
  - **default(none), shared(), private()**
- **Work sharing: loops, sections [section]:**
  - **C/C++: #paragma omp for or #pragma omp parallel for**
  - ✓ **Fortran:**
    - **!$omp do … !$omp end do**
    - **!$omp parallel do … !$omp end parallel do**

Application of OpenMP: compute π (3.14)

Mathematically:

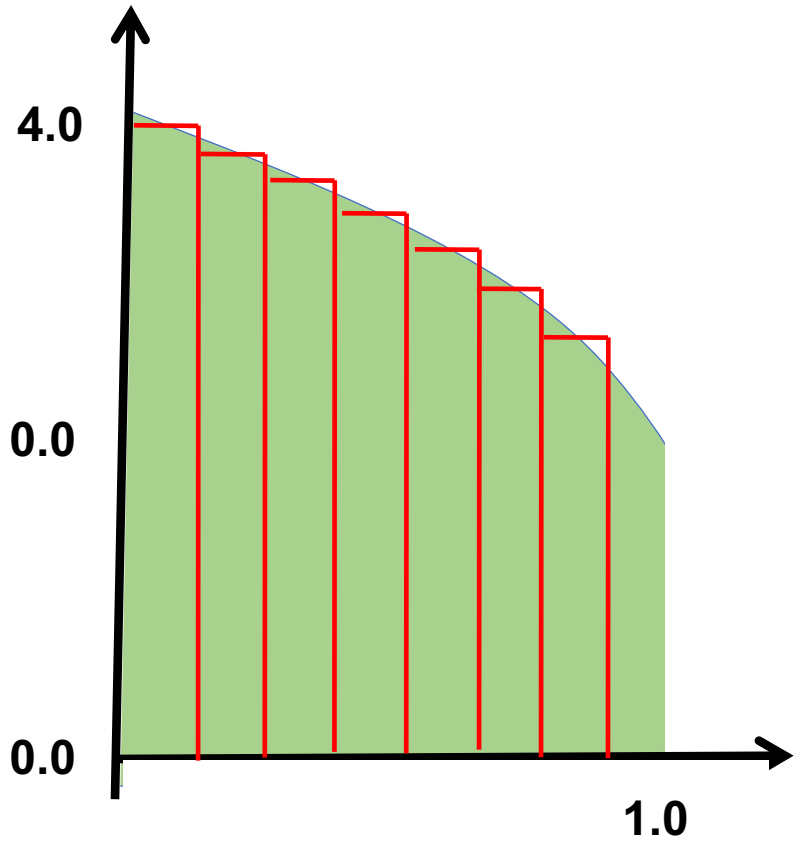
$$\int_0^1 \frac{4}{1+x^2}\,dx = \pi$$

This function can be approximated by a sum of rectangles:

$$\sum_{i=1}^{n} F(Xi)\,\Delta X \approx \pi$$

Where each rectangle has a width ΔX and height $F(X_i)$ at the middle of the interval [i, i+1]

Numerical integration:



Serial version: compute π (3.14)

- **Directory:** Example_02
- **Files:** compute_pi_c_seq.c; compute_pi_f90_seq.f90

C/C++

```
double x, pi, sum;
int i;
sum = 0.0;
for (i = 0; i < nb_steps; i++) {
      x = (i + 0.5) * step;
      sum += 1.0/(1.0 + x * x);
      }
pi = 4.0 * sum * step;
```

Fortran

```
real(8) :: pi, sum, x
integer :: i
sum = 0.0d0
do i = 0, nb_steps
    x = (i + 0.5) * step
    sum = sum + 1.0/(1.0 + x * x)
end do
pi = 4.0 * sum * step
```

Compile & run the code

```
$ gcc compute_pi_c_seq.c
$ ./a.out
pi = 3.14159
```

Compile & run the code

```
$ gfortran compute_pi_f90_seq.f90
$ ./a.out
pi = 3.14159
```

OpenMP version: compute π (3.14)

File: Example_02	File: Example_02
compute_pi_c_omp-template.c	compute_pi_f90_omp-templtae.f90

To Do:

- **Add the compiler directives to create the OpenMP version:**
  - **C/C++: #pragma omp parallel { …….. }**
  - **Fortran: !$omp parallel ….. !$omp end parallel**
- Include the header: **<omp.h>** in **C/C++**; and **use omp_lib** in **Fortran**
- **Variables:**
  - **default(none), shared(), private()**
- **Optionally: omp_get_wtime()**

Compile the code

```
$ gcc –fopenmp compute_pi_c_omp-template.c
$ gfortran –fopenmp compute_pi_f90_omp-template.f90
```

Race condition and false sharing

File: Example_02

compute_pi_c_omp_race.c

C/C++

```
#pragma omp parallel default(none)
private(i) shared(x,sum)  {
  int i; double x;
  for (i = 0; i < nb_steps; i++) {
        x = (i + 0.5) * step;
        sum += 1.0/(1.0 + x * x);
        }
}
pi = 4.0*sum*step;
```

File: Example_02

compute_pi_f90_omp_race.f90

Fortran

```
!$omp parallel default(none)
private(i) shared(x,sum)

do i = 0, nb_steps
     x = (i + 0.5) * step
     sum = sum + 1.0/(1.0 + x * x)
end do
!$omp end parallel
pi = 4.0*sum*step
```

Compile and run the code

```
$ gcc –fopenmp compute_pi_c_omp_race.c
$ gfortran –fopenmp compute_pi_f90_omp_race.f90
```

Race Condition in OpenMP

Compile & run the program	Compile & run the program
compute_pi_c_omp_race.c	compute_pi_f90_omp_race.f90

Run the program

```
$ ./a.out
The value of pi is [  9.09984 ]; Computed using [ 20000000 ] steps in [  9.280 ] s.
$ ./a.out
The value of pi is [ 11.22387 ]; Computed using [ 20000000 ] steps in [ 11.020 ] s.
$ ./a.out
The value of pi is [  5.90962 ]; Computed using [ 20000000 ] steps in [  5.640 ]  s.
$ ./a.out
The value of pi is [  8.89411 ]; Computed using [ 20000000 ] steps in [  8.940 ]  s.
$ ./a.out
The value of pi is [ 10.94186 ]; Computed using [ 20000000 ] steps in [ 10.870 ] s.
$ ./a.out
The value of pi is [ 10.89870 ]; Computed using [ 20000000 ] steps in [ 11.030 ] s.
```

Wrong answer & slower than serial program

How to solve this problem?

SPMD: Single Program Multiple Data

SPMD:

- a technique to achieve parallelism.
- each thread receive and execute a copy of a same program.
- each thread will execute a copy as a function of its ID.

➢ Cyclic Distribution

Thread 0: 0, 3, 6, 9 ….
Thread 1: 1, 4, 7, 10, …
Thread 2: 2, 5, 8, 11, …

C/C++

```
#pragma omp parallel
{
    for (i=0; I < n; i++) { computation[i]; }
}
```

SPMD

```
#pragma omp parallel
{
int numthreads = omp_get_num_threads();
int ID = omp_get_thread_num();
for (i=0+ID; I < n; i+=numthreads) {
        computation[i][ID]; }
}
```

SPMD: Single Program Multiple Data

File: Example_03/	File: Example_03/
compute_pi_c_spmd-template.c	compute_pi_f90_spmd-template.f90

- **Add the compile directives to create the OpenMP version:**
  - **C/C++: #pragma omp parallel { …….. }**
  - **Fortran: !$omp parallel ….. !$omp end parallel**
- Include the header: **<omp.h>** in **C/C++**; and **use omp_lib** in **Fortran**
- **Promote the variable sum to an array: each thread will compute a sum as a function of its ID; then compute a global sum.**
- **Compile and run the program.**

SPMD: Single Program Multiple Data

File: Example_03/

compute_pi_c_spmd_simple.c

C/C++

```
#pragma omp parallel
{
Int nthreads = omp_get_num_threads();
Int ID = omp_get_thread_num();
sum[id] = 0.0;
for (i = 0+ID; i < nb_steps; i+=nthreads) {
   x = (i + 0.5) * step;
   sum[ID] = sum[ID] + 1.0/(1.0 + x*x); }
}
compute_tot_sum(); [ i = 1 to nthreads]
pi = 4.0 * tot_sum * step;
```

File: Example_03/

compute_pi_f90_spmd_simple.f90

Fortran

```
!$omp parallel
nthreads = omp_get_num_threads()
ID = omp_get_thread_num();
sum(id) = 0.0
do i = 1+ID, nb_steps, nthreads
     x = (i + 0.5) * step;
     sum(ID) = sum(ID) + 1.0/(1.0 + x*x);
end do
!$omp end parallel
compute_tot_sum [ i = 1 to nthreads]
pi = 4.0 * tot_sum * step
```

Compile and run the code: the answer is correct but very slow than serial

SPMD: Single Program Multiple Data

Execute the program

```
$ a.out
The value of pi is [  3.14159; Computed using [ 20000000] steps in [ 0.4230]  seconds
The value of pi is [  3.14166; Computed using [ 20000000] steps in [ 1.2590]  seconds
The value of pi is [  3.14088; Computed using [ 20000000] steps in [ 1.2110]  seconds
The value of pi is [  3.14206; Computed using [ 20000000] steps in [ 1.9470]  seconds
```

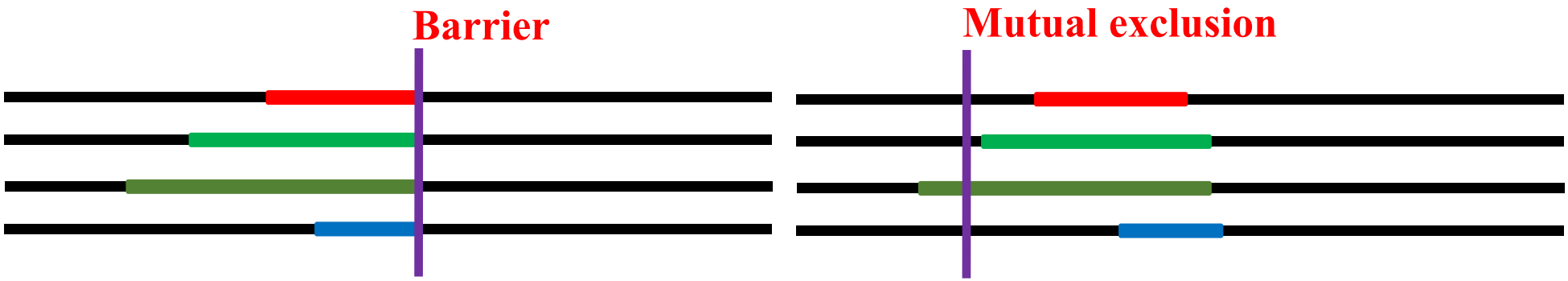
- The answer is correct
- Slower than serial program

- How to speed up the execution of pi program?
  - Synchronization
  - Control how the variables are shared to avoid race condition

Synchronization in OpenMP

Synchronization: Bringing one or more threads to a well defined point in their execution.

- **Barrier:** each thread wait at the barrier until all threads arrive.
- **Mutual exclusion:** one thread at a time can execute.



High level constructs:
- **critical**
- **atomic**
- **barrier**
- **ordered**

Low level constructs:
- **flush**
- **locks:**
  - simple
  - nested

Synchronization:
- can **reduce the performance**.
- cause **overhead** and cost a **lot**.
- more barriers will **serialize the program**.
- **Use it when needed.**

Synchronization: barrier

C/C++

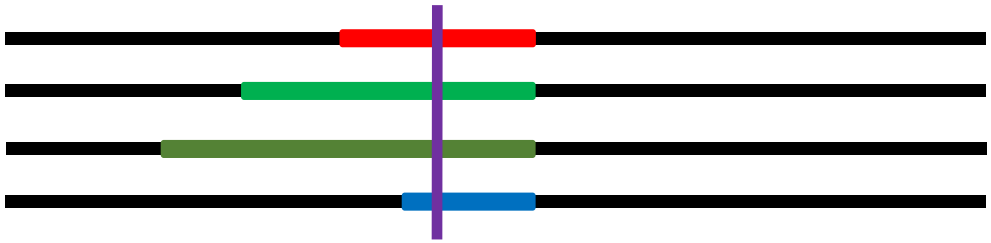
```
#pragma omp parallel
{
    int ID = omp_get_thread_num();
    A[ID] = Big_A_Computation(ID);

#pragma omp barrier
    A[ID] = Big_B_Computation(A,ID);

}
```

Fortran

```
!$omp parallel
    int ID = omp_get_thread_num()
    A[ID] = Big_A_Computation(ID)

!$omp barrier
    A[ID] = Big_B_Computation(A,ID)
!$omp end barrier

!$omp end parallel
```

- **Barrier:**

each thread **wait at the barrier** until **all threads arrive**.



Synchronization: critical

C/C++

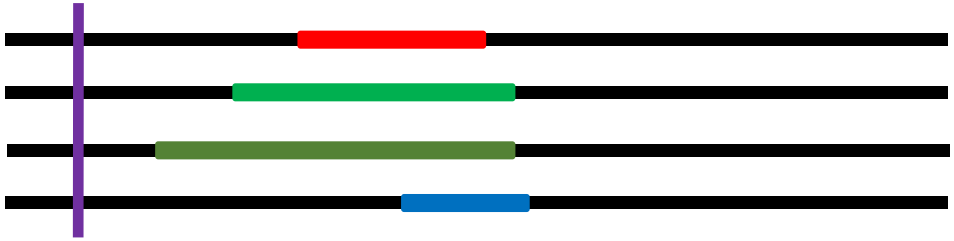
```
#pragma omp parallel
{
  float B; int i, id, nthrds;
  id = omp_get_thread_num();
  nthrds = omp_get_num_threads();
  for (i=id;I < niters; i+=nthrds) {
       B = big_calc_job(i);
       #pragma omp critical
        res += consume (B);
        }
}
```

Fortran

```
!$omp parallel
    real(8) :: B; integer :: i, id, nthrds
    id = omp_get_thread_num()
    nthrds = omp_get_num_threads()
    do I = id, niters, nthrds
         B = big_calc_job(i);
!$omp critical
         res = res + consume (B);
!$omp end critical
     end do
!$omp end parallel
```

Mutual exclusion:

- **Critical:** only one thread at a time can enter a critical region (calls consume())



Synchronization: atomic construct

Synchronization: atomic (basic form),

- **Atomic provides mutual exclusion but only applies to the update of a statement of a memory location: update of X variable in the following example.**

C/C++

```
#pragma omp parallel
{
    double tmp, B;
    B = DOIT();
    tmp = big_calculation(B);
    #pragma omp atomic
        X += tmp;
}
```

Fortran

```
!$omp parallel
real(8) :: tmp, B
B = DOIT()
tmp = big_calculation(B)
!$omp atomic
    X = X + tmp

!$omp end parallel
```

Reduction construct

❖ Aggregating values from different threads is a common operation that OpenMP has a special *reduction variable*

➢ Similar to private and shared
➢ Reduction variables support several types of operations: + - *

❖ Syntax of the reduction clause: reduction (op : list)

❑ Inside a parallel or a work-sharing construct:
  ➢ A local copy of each list of variables is made and initialized depending on the "op" (e.g. 0 for "+").
  ➢ Updates occur on the local copy.
  ➢ Local copies are reduced into a single value and combined with the original global value.
  ➢ The variables in "list" must be shared in the enclosing parallel region.

Example of reduction in OpenMP

C/C++

```
Int MAX = 10000;
double ave=0.0;
A[MAX]; int i;

#pragma omp parallel for
reduction (+:ave)
    for (i=0;I < MAX; i++) {
          ave + = A[i];
    }
    ave = ave / MAX
```

Fortran

```
real(8) :: ave = 0.0;
integer :: MAX = 10000
real :: A(MAX); integer :: I

!$omp parallel do reduction(+:ave)
    do i = 1, MAX
        ave = ave + A(i)
     end do
!$omp end parallel do
ave = ave / MAX
```

- The variable ave is initialized outside the parallel region.
- Inside the parallel region:
  - Each thread will have its own copy , initialize it, update it.
  - At the end, all the local copies will be reduced to a final result.

Critical and reduction

Files: Example_04/

C/C++: compute_pi_c_omp_critical-template.c
compute_pi_c_omp_reduction-template.c

F90: compute_pi_f90_omp_critical-template.f90
compute_pi_f90_omp_reduction-template.f90

- **Start from the sequential version of pi program, the add the compile directives to create the OpenMP version:**
  - **C/C++: #pragma omp parallel { …….. }**
  - **Fortran: !$omp parallel ….. !$omp end parallel**
  - Include the header: **<omp.h>** in **C/C++**; and **use omp_lib** in **Fortran**
- **Use the SPMD pattern with critical construct in one version and reduction in the second one.**
- **Compile and run the programs.**

Critical and reduction

Example of output

```
$ a.out
The Number of Threads = 1
The value of pi is [  3.14159 ]; Computed using [ 20000000 ] steps in [  0.40600 ]  seconds
The Number of Threads = 2
The value of pi is [  3.14159 ]; Computed using [ 20000000 ] steps in [  0.20320 ]  seconds
The Number of Threads = 3
The value of pi is [  3.14159 ]; Computed using [ 20000000 ] steps in [  0.13837 ]  seconds
The Number of Threads = 4
The value of pi is [  3.14159 ]; Computed using [ 20000000 ] steps in [  0.10391 ]  seconds
```

- **Results:**
  - **Correct results.**
  - **The program run faster (4 times faster using 4 cores).**

Summary

OpenMP:

- create threads:
  - C/C++ #pragma omp parallel { … }
  - Fortran: !$omp parallel … !$omp end parallel
- Work sharing: (loops and sections).
- Variables: default(none), private(), shared()
- Environment variables and runtime library.

omp_set_num_threads()
omp_get_num_threads()
omp_get_thread_num()
omp_get_wtime()

Few construct of OpenMP:

- single construct
- barrier construct
- atomic construct
- critical construct
- reduction clause

For more advanced runtime library clauses
And constructs, visit:
http://www.openmp.org/specifications/

Concluding

OpenMP - API:

- Simple parallel programming for shared memory machines.
- Speed up the executions (but not very scalable).
- compiler directives, runtime library, environment variables.

Add the directives and test:

- Define concurrent regions that can run in parallel.
- Add compiler directives and runtime library.
- Control how the variables are shared.
- Avoid the false sharing and race condition by adding synchronization clauses (chose the right ones).
- Test the program and compare to the serial version.
- Test the scalability of the program as a function of threads.

More readings

- **OpenMP:** http://www.openmp.org/
- **Compute Canada Wiki:** https://docs.computecanada.ca/wiki/OpenMP
- **Reference cards:** http://www.openmp.org/specifications/
- **OpenMP Wiki:** https://en.wikipedia.org/wiki/OpenMP
- **Examples:**

http://www.openmp.org/updates/openmp-examples-4-5-published/

- **Contact:** support@westgid.ca
- **WestGrid events:** https://www.westgrid.ca/events

More readings

Thank you