COMP4300 - Course Update

- **Assignment 1**
  - Marking nearly complete

- **Assignment 2**
  - Released on 24 April
  - Due 26/05/2025, 11:55PM
  - Start early

OpenMP: Part I

OpenMP Reference Material

- **Using OpenMP – The Next Step**, R. van der Pas, E. Stotzer, and C. Terboven, Chapter 1
- http://www.openmp.org/
- *Introduction to High Performance Computing for Scientists and Engineers*, Hager and Wellein, Chapter 6 & 7
- *High Performance Computing*, Dowd and Severance, Chapter 11
- *Introduction to Parallel Computing, 2nd Ed*, A. Grama, A. Gupta, G. Karypis, V. Kumar
- *Parallel Programming in OpenMP*, R. Chandra, L.Dagum, D.Kohr, D.Maydan. J.McDonald, R.Menon

History of Concurrent Programming

Fork

- The concept of "fork" originated in Unix operating systems.
- Forking was a fundamental mechanism for multitasking in Unix.
- The fork() system call is used to create a new process by duplicating the existing process.

Threads

- As computing needs grew, the limitations of process-based concurrency became apparent, particularly the overhead associated with creating and managing processes.
- Threads enabled finer-grained parallelism and improved performance for applications requiring concurrent execution of tasks.

OpenMP

- OpenMP (Open Multi-Processing) is an API that supports multi-platform shared memory multiprocessing programming in C, C++, and Fortran.
- OpenMP uses compiler directives, library routines, and environment variables to control parallelism.

Shared Memory Parallel Programming

- Explicit thread programming is messy
  - low-level primitives
  - complex data scoping and initialization not easy to port
  - significant amount of boiler-plate code
  - used by system programmers, but …. application programmers have OpenMP!
- Many application codes can be supported by higher level constructs with the same performance
  - led to proprietary directive based approaches of Cray, SGI, Sun, etc.
- OpenMP is an API for shared memory parallel programming targeting Fortran, C and C++
  - standardizes the form of the proprietary directives
  - avoids the need for explicitly setting up mutexes, condition variables, data scope, and a good part of explicit initialization
  - When you compile an OpenMP program, the compiler often translates OpenMP directives into pthreads calls to manage parallel execution

OpenMP

- Specifications maintained by OpenMP Architecture Review Board (ARB)
  - members include AMD, Intel, Fujitsu, IBM, NVIDIA
- Versions 1.0 (Fortran ’97, C ’98), 1.1 and 2.0 (Fortran ’00, C/C++ ’02), 2.5 (unified Fortran and C, 2005), 3.0 (2008), 3.1 (2011), 4.0 (2013), 4.5 (2015), 5.0 (2018), 6.0 (2024)
- Comprises compiler directives, library routines and environment variables
  - C directives (case sensitive)

```
#pragma omp directive_name [clause-list]
```

  - library calls begin with omp_

```
void omp_set_num_threads(nthreads)
```

  - environment variables begin with OMP_

```
export OMP_NUM_THREADS=4
```

- OpenMP requires compiler support
  - set `-fopenmp` (gcc) or `-qopenmp` (icc) compiler flags

The `Parallel` Directive

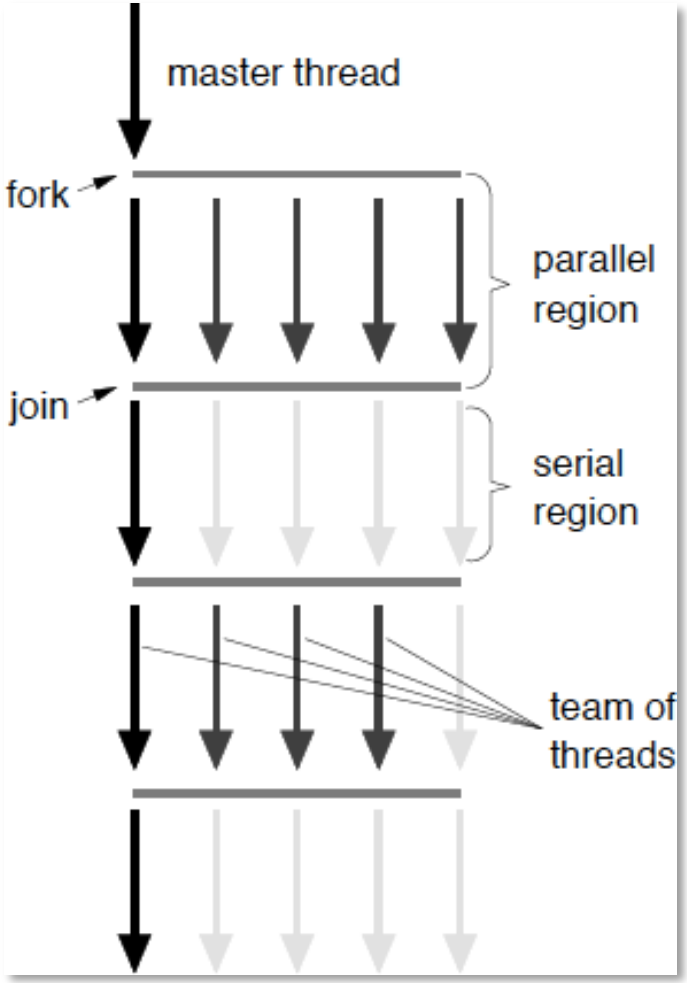
- OpenMP uses a fork/join model, i.e. programs execute serially until they encounter a parallel directive:
  - this creates a group of threads
  - the number of threads is dependent on an environment variable or is set via function call
  - the main thread becomes master with thread id 0

```
#pragma omp parallel [ clause - list ]
    /* structured block */
```

- Each thread executes the *structured block*
- In C/C++ this is a brace-enclosed (`{ code }`) sequence of statements and declarations.

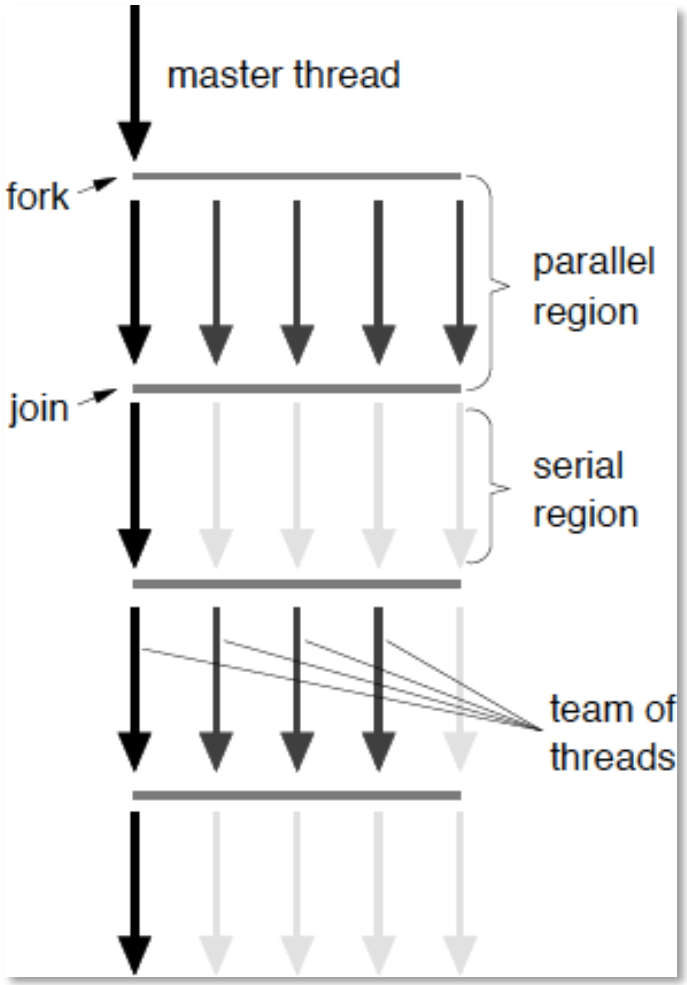
The OpenMP Execution Model

- An OpenMP starts in serial mode with one thread executing the serial code (*master thread*)
- At the beginning of the parallel region additional threads are created (***fork*ing** from the master) by the runtime system forming a *thread team*
- All threads are active in the parallel regions, executing the program in parallel.
- At the end of the parallel region threads are ***joined***, with only the master continuing through the serial portion.
- **This is called the *fork-join* model.**



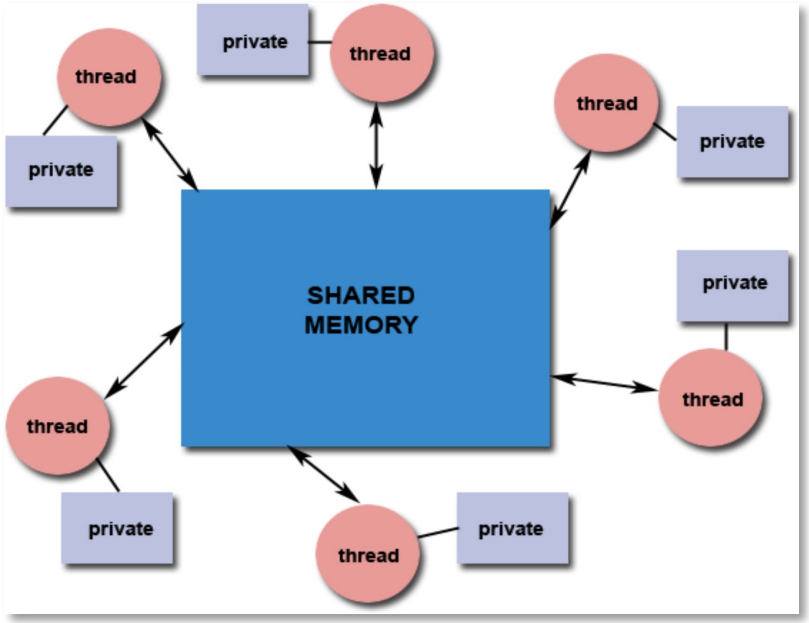
The OpenMP Execution Model

- The number of threads execution in the parallel region can be set through the `OMP_NUM_THREADS` environment variable.
- If the number of threads need to be more dynamic, the `omp_set_num_threads` may be used *prior* to a parallel region.
- An alternative is to use the `num_threads<nt>` clause on the `parallel` directive.
- Because of the join operation, the end of the parallel region is an *implicit synchronization point* (barrier).



The OpenMP Memory Model

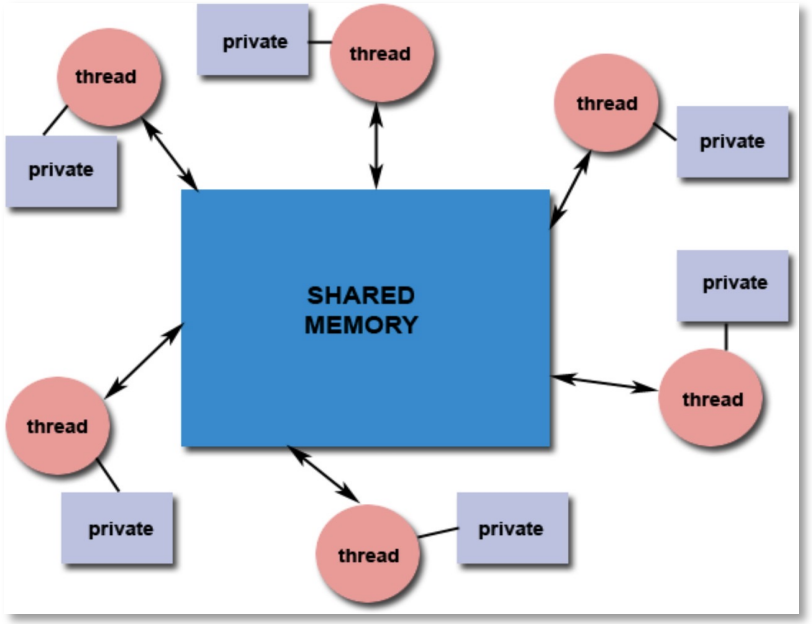
- Underlying the OpenMP standard is the `pthreads` memory model, but the distinction between *private* and *shared* is clearer.
- Whether a variable is private or shared as well as their initialization can be defined by *default rules*
- These can also be explicitly controlled through appropriate clauses on a construct.
- It is recommended to <u>not</u> rely on the default rules and explicitly label or “scope" variables.



The OpenMP Memory Model

Private and Shared Variables

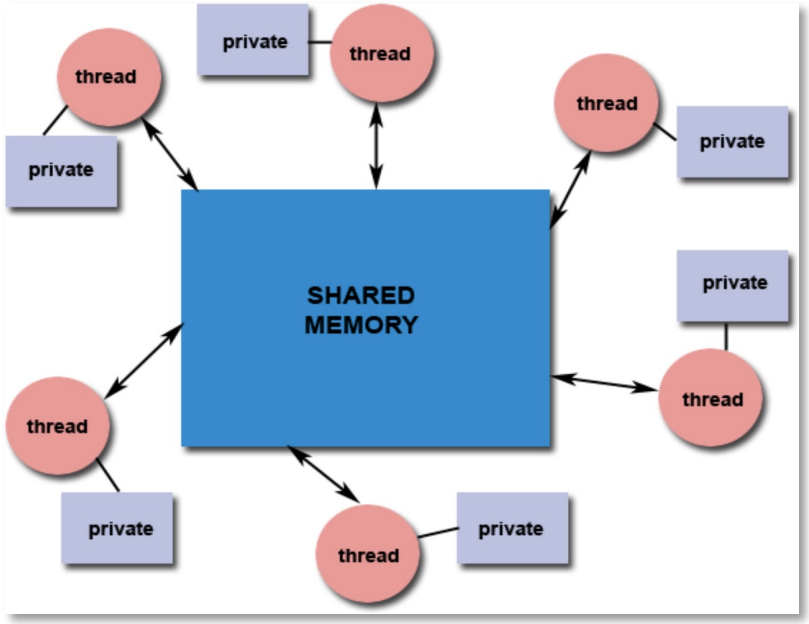
- Private variables can be accessed only by the owning thread, no other thread may interfere.
- Threads may even use the same name for a private variable without the risk of any conflict.
- Each thread has read and write access to the same shared variable, that is only one instance of a given shared variable exists.
- Global or static variables are shared by default.



The OpenMP Memory Model

Default Rules

- Variables declared outside the parallel region are shared by default.
- Global and static variables are also shared by default.
- Variables declared inside the parallel region are private by default.



Data Sharing Clauses

- The `private (shared)` clause may be used to make a variable thread private (shared).
- One needs to be careful with initialization.
- The `firstprivate` clause guarantees that all threads have a pre-initialized copy of a variable
- The `default` clause is used to give a default data sharing attribute (`none, shared, private`) to all variables.
- When `default(none)` is used, the programmer is forced to specify data-sharing attributes for all variables in the construct.

```
int x = 5; int y = 20;
int z[ NUM_THREADS ] = {0};
# pragma omp parallel default ( none ) shared ( z)
   private ( x) firstprivate ( y)
{
 x = 10; // x is undefined on entry , but now set
    to 10
 z[ omp_get_thread_num ()] = omp_get_thread_num ();
 int w = x + y+ z[ omp_get_thread_num () ]; // y pre
    - initialized to a value of 20
 ...
 y = 30 // firstprivate var may be modified
}
```

Data Sharing Attributes

Default Rules

- Variables declared outside the parallel region are **shared** by default.
- Global and static variables are also **shared** by default.
- Variables declared inside the parallel region are **private** by default.

```
int g = 0; // g is shared
int main (){
 int i = 0; // i is shared
 static int a = 7; // a is shared
 # pragma omp parallel
 {
  int b = a + i + g; // b is private
  ...
 }
return 0;
}
```

OpenMP:The Work-Sharing Directives

- Used to distribute work among threads in a team.
- They specify the way the work has to be distributed among threads.
- Work-sharing directive must bind to a parallel region, otherwise is simply ignored.
- Work-sharing constructs do not have a barrier at entry.
- By default, a barrier is implemented at the end of the work-sharing region. The programmer can suppress the barrier with use of the nowaitclause.

Functionality	Syntax in C/C++	Syntax in Fortran
Distribute iterations over the threads	**#pragma omp for**	**!$omp do**
Distribute independent work units	**#pragma omp sections**	**!$omp sections**
Only one thread executes the code block	**#pragma omp single**	**!$omp single**
Parallelize array-syntax		**!$omp workshare**

The `for` Work-Sharing Directives

Used in conjunction with `parallel` directive to partition the `for` loop immediately afterwards

- The loop index (i) is made private by default
- Only two directives plus the sequential code (code is easy to read/maintain)
- Limited to loops where number of iterations can be counted

```
# pragma omp parallel shared ( n)
{
# pragma omp for
for ( i = 0; i < n; i ++) {
    printf (" Thread % d , iteration % d\ n",
              omp_get_thread_num , i);
    }
} /* End of parallel region */
```

There is implicit synchronization at the end of the loop

- Can add a `nowait` clause to prevent synchronization

The `for` Work-Sharing Directives

- The order in which threads execute is not predictable (OS scheduled).
- The way to map iterations to threads can be specified by the programmer (see later `schedule` clause).
- If the programmer does not specify the mapping between threads and iterations, the compiler decides which strategy to use.

```
Thread 0 executes loop iteration 0
Thread 0 executes loop iteration 1
Thread 0 executes loop iteration 2
Thread 3 executes loop iteration 7
Thread 3 executes loop iteration 8
Thread 2 executes loop iteration 5
Thread 2 executes loop iteration 6
Thread 1 executes loop iteration 3
Thread 1 executes loop iteration 4
```

The `sections` Work-Sharing Directives

- Consider partitioning of fixed number of tasks across threads
- Each section must be a structured block that is independent from the other sections.
- Separate threads will run `taskA` and `taskB`
- Illegal to branch in or out of section blocks

Note:

- Much less common than `for` loop partitioning
- Explicit programming naturally limits number of threads (scalability)
- Potential load imbalance

```
# pragma omp parallel
{
  # pragma omp sections
  {
    # pragma omp section
        task A ()

    # pragma omp section
        task B ()

  } /* End of sections block */

} /* End of parallel region */
```

The `single` Work-Sharing Directives

- This directive specifies that only one thread must execute the code in the structured block following it.
- It does not state which thread should execute the code.

```
# pragma omp parallel shared ( a, b, n)
{
  # pragma omp single
  {
     a = 10;
  } /* A barrier is automatically inserted here */
  # pragma omp for
  for ( i = 0; i < n; ++i)
  {
    b[ i] = a;
  }/* Another barrier is automatically inserted here */
}
```

Combined `parallel` Work-Sharing Directives

- When there is only one work-sharing directive it can be combined with the `parallel` one to improve readability.
- Only clauses that are allowed by both the `parallel` and the specific work-share directive are allowed, otherwise the code is illegal.
- The compiler may optimize code further (*e.g.* remove redundant barriers).

Full version	Combined construct

#pragma omp parallel
{
  #pragma omp for
  `for-loop`
}
	#pragma omp parallel for
	  `for-loop`

#pragma omp parallel
{
#pragma omp sections
{
  [**#pragma omp section**]
  structured block
  [**#pragma omp section**
  structured block]
  ...
}
}
	#pragma omp parallel sections
	{
	  [**#pragma omp section**]
	  structured block
	  [**#pragma omp section**
	  structured block]
	  ...
	}

Demo
OpenMP – Pi calculation

- Monte Carlo Pi calculation code
- Get the number of threads from the environment variable `OMP_NUM_THREADS`
- Detailed performance information:
  - Total Execution Time
  - Initialization Time
  - Computation Time
  - Finalization Time
- Each timing section uses omp_get_wtime() which is thread-safe and provides high-resolution timing information appropriate for OpenMP applications
- At the end, the code calculates and displays:
  - Speedup = Sequential Time / Parallel Time
  - Parallel Efficiency = Speedup / Number of Threads

Demo
OpenMP – Pi calculation

- Monte Carlo Pi calculation code scales well using OpenMP
- Adding more threads than processors delivers better performance for this problem.
  - Thread switching overhead is low.
- Code changes are minimal: -

```
#pragma omp parallel for firstprivate(x, y, z) reduction(+:count)
```