PARALLEL PROGRAMMING...

Parallel Programming: Overview

SESSION 3/6

GOAL

Programming Interface for parallel computing

OpenMP (Open Multi-Processing)

Programming interface for parallel computing

병렬 컴퓨팅을 위한 프로그래밍 인터페이스

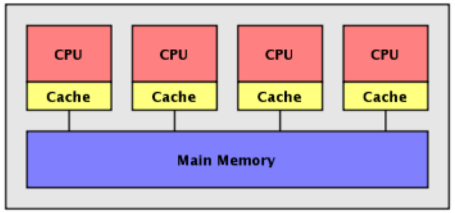
OpenMP (Open Multi-Processing)

OpenMP (Open Multi-Processing)

OpenMP is a programming interface for parallel computing on **shared memory architecture**.

A set of compiler directives and a runtime library

```
#pragma omp parallel num_threads(4)
#include <omp.h>
```



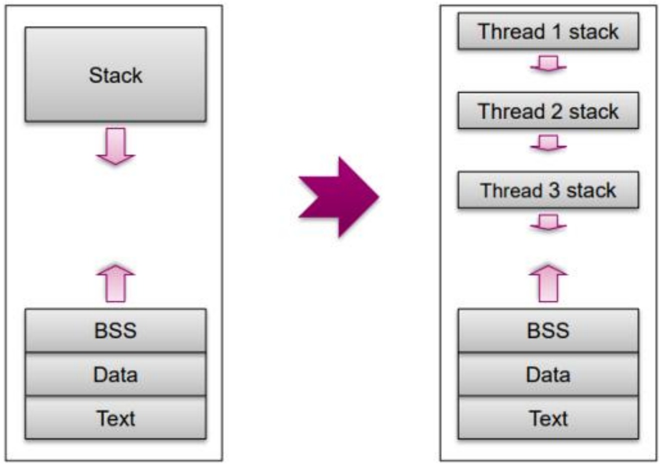
- **It allows you to manage:**

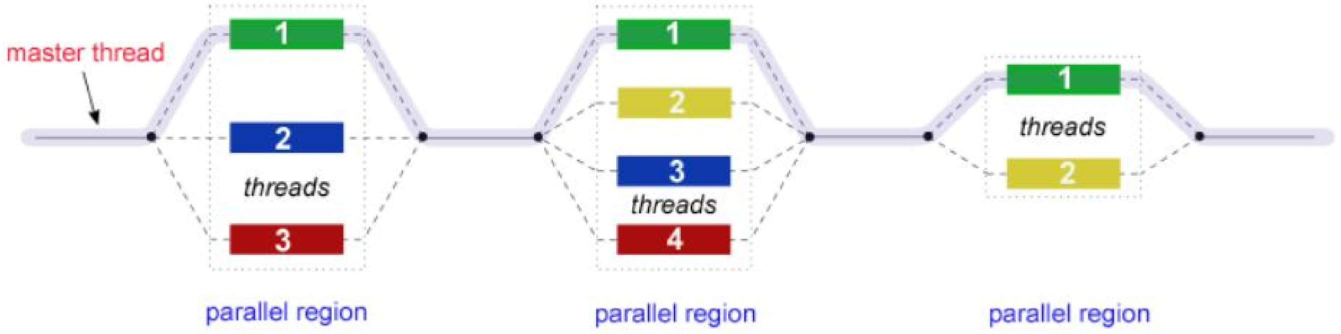
- ➢ the creation of light processes
- ➢ the sharing of work between these lightweight processes
- ➢ synchronizations (explicit or implicit) between all light processes
- ➢ the status of the variables (private or shared).

OpenMP (Open Multi-Processing)

OpenMP is based on **Fork/Join model**

- When program starts, one Master thread is created
- Master thread executes sequential portions of the program
- At the beginning of parallel region, master thread forks new threads
- All the threads together now forms a “team”
- **At the end** of the parallel region, **the forked threads die !**





OpenMP (Open Multi-Processing)

The OpenMP API consists of

- compiler directives (for insertion ***into sequential*** Fortran/C/C++$code)
- a few library routines
- some environment variables

Advantages:

- User-friendly
- Incremental parallelization of a serial code
- Possible to have a single source code for both serial and parallelized versions

Disadvantages:

- Relatively limited user control
- Most suitable for parallelizing loops (data parallelism)
- Performance?

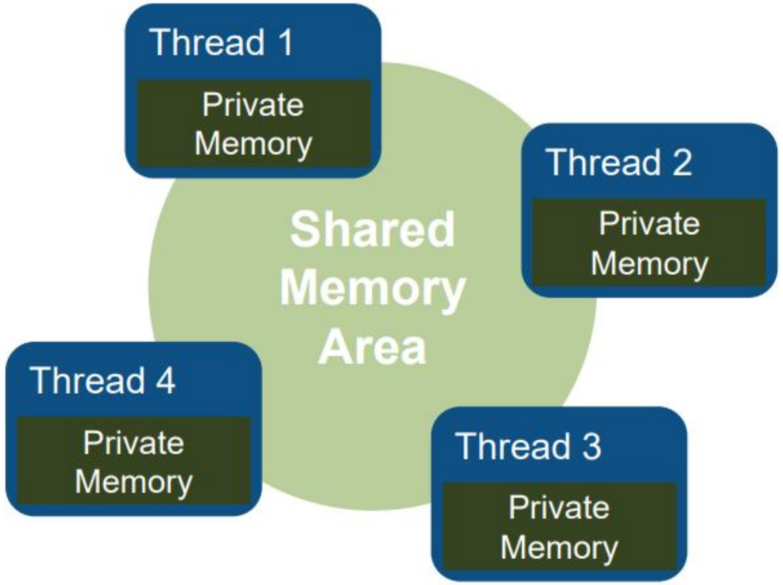
OpenMP (Open Multi-Processing)

What is a **Shared-Memory Program**?

- One process that spawns multiple threads

- Threads can communicate via shared memory
  - ➢ Read/Write to shared variables
  - ➢ Synchronization can be required!

- OS decides how to schedule threads



OpenMP (Open Multi-Processing)

- **Shared memory model**
  - ➢ Threads communicate by accessing shared variables.

- **The sharing is defined syntactically**
  - ➢ Any variable that is seen by two or more threads is shared.
  - ➢ Any variable that is seen by one thread only is private.

- **Race conditions possible**
  - ➢ Use synchronization to protect from conflicts.
  - ➢ Change how data is stored to minimize the synchronization.

OpenMP (Open Multi-Processing): Why ?

- **Multicore CPUs are everywhere:**
  - ➢ Servers with over 100 cores today and more.
  - ➢ Even smartphone CPUs have 8 cores.

- **Multithreading, natural programming model**
  - ➢ All processors share the same memory.
  - ➢ Threads in a process see same address space.
  - ➢ Many shared-memory algorithms developed.

- **Multithreading is hard**
  - ➢ Lots of expertise necessary.
  - ➢ Deadlocks and race conditions.
  - ➢ Non-deterministic behavior makes it hard to debug.

OpenMP: Process and thread: whatis the difference ?

- You need an **existing process** to **create a thread.**

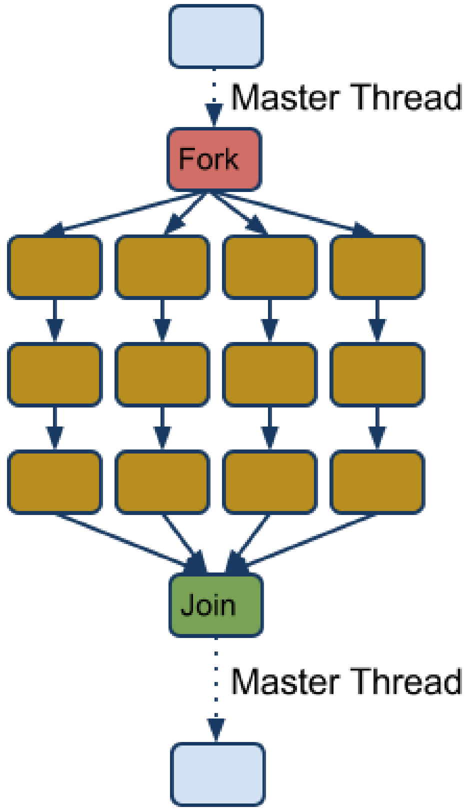
- **Each process** has at least **one thread of execution**.

- **A process** has its **own virtual memory space** that **cannot be accessed by other processes running** on the same or on a different processor.

- **All threads created** by a process **share the virtual address space of that process**.
  - ➢ They read and write to the same address space in memory.
  - ➢ They share the same process and user ids, file descriptors, and signal handlers.
  - ➢ They have their own program counter value and stack pointer, and can run independently on several processors.

OpenMP: Terminology and behavior

- **OpenMP Team** = **Master** + **Worker**
- **Parallel Region** is a block of code executed by all threads simultaneously (*has implicit barrier*)
  - The master thread always has thread id **0 !**
  - Parallel regions can be nested.
  - If **clause** can be used **to guard the parallel region.**



OpenMP: General Code Structure

```
#include <omp.h>

main ()
{
        int var1, var2, var3;
        //serial code

        //start of a parallel region
        #pragma omp parallel private(var1, var2) shared(var3)
        {...}

        //more serial code
        {...}

        //another parallel region
        #pragma omp parallel
        {…}
        }
```

OpenMP: Constructs Parallel Region

Parallel region

- Thread creates team, and becomes master (id 0).
- All threads run code after.
- Barrier at end of parallel section.

```
#pragma omp parallel [clause ...]
                     if (scalar_expression)
                     private (list)
                     shared (list)
                     default (shared | none)
                     firstprivate (list)
                     lastprivate (list)
                     reduction (operator: list)
                     num_threads (integer)


   structured_block
```

(not a complete list)

OpenMP: Parallel Clauses

```
#pragma omp parallel if (scalar_expression)
```

Only execute in parallel.
Otherwise serial.

```
#pragma omp parallel private (list)
```

Data local to thread.
Value are not guaranted to be defined on exit (even if defined before)
No storage associated with original object
Use firstprivate and/or lastprivate clause to override

```
#pragma omp parallel firstprivate (list)
```

Variables in list are private.
Initialized with the value the variable had before entering the construct.

```
#pragma omp parallel for lastprivate (list)
```

Only in for loops
Variables in list are private.
The thread that executes the sequentially last iteration updates the value of the variables in the list.

OpenMP: Parallel Clauses

```
#pragma omp shared (list)
```

Data is accessible by all threads in team.
All threads access same address space.

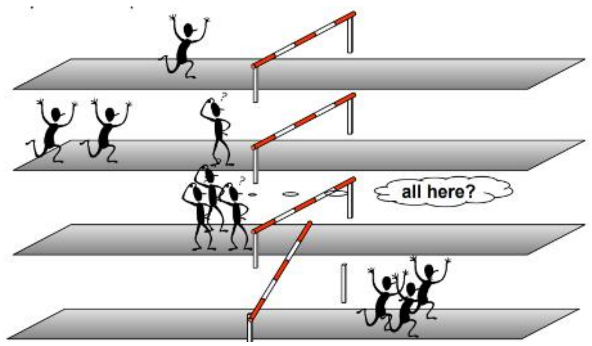
Improperly scoped variables are big source of OMP bugs
- Shared when should be private
- Race condition

```
#pragma omp default (shared | none)
```

Tip: *Safest is to use default (none) and declare by hand.*

OpenMP: Barrier

- When a thread reaches a barrier it only continues after all the threads in the same thread team have reached it.
- Each barrier must be encountered by all threads in a team, or none at all
- The sequence of work-sharing regions and barrier regions encountered must be same for all threads in team
- Implicit barrier at the end of: do, parallel, single, workshare

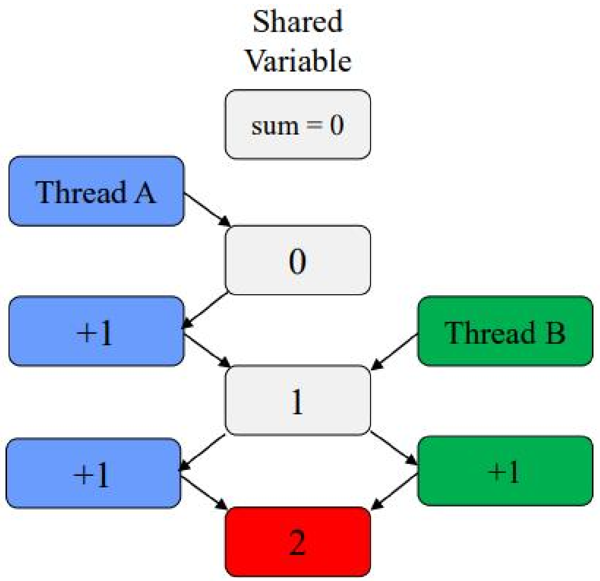


OpenMP: Caution Race Condition

When multiple threads simultaneously read/write
Multiple OMP solutions :

- **R**eduction
- **A**tomic
- **C**ritical

```
#pragma omp parallel for private(i) shared(sum)
  for (i=0; i<N; i++) {
    sum += i;
  }
```



Should be 3!

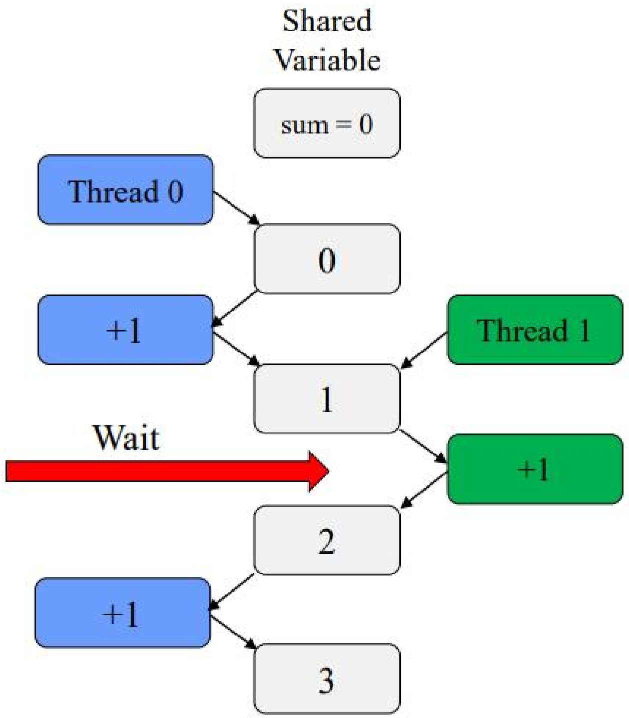
OpenMP: Critical Section

One solution: use **critical**

Only one tread at a time can execute a critical section

```
#pragma omp critical
   {
     sum += i;
   }
```

Downside ?
YES SLOOOOWWW
Overhead and serialization

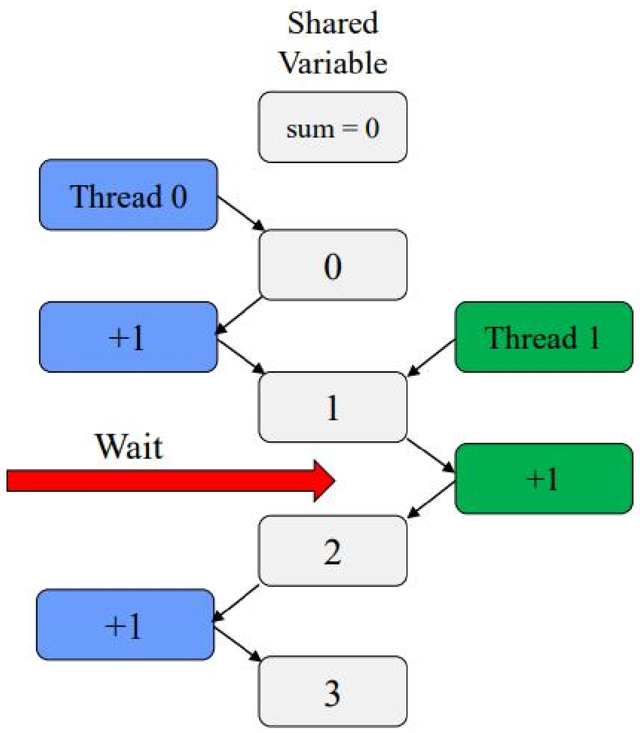


OpenMP: Atomic

Atomics like "mini" critical
Only one line
Certain limitations

```
#pragma omp atomic
    sum += i;
```

Hardware controlled
Less overhead the critical



OpenMP: Reduction

```
#pragma omp reduction (operator:variable)
```

- **Avoids race condition**
- Reduce variable must be shared
- Makes variable private, then performs operator at end of loop
- operator cannot be overloaded (c++)
  - One of: +,*,-,/ (and &,^,|,&&,||)
  - OpenMP 3.1: added min and max for c/c++

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

int main() {

  int i;
  const int N = 1000;
  int sum = 0;

#pragma omp parallel for private(i) reduction(+: sum)
  for (i=0; i<N; i++) {
    sum += i;
  }

  printf("reduction sum=%d (expected %d)\n", sum, ((N-1)*N)/2);
```

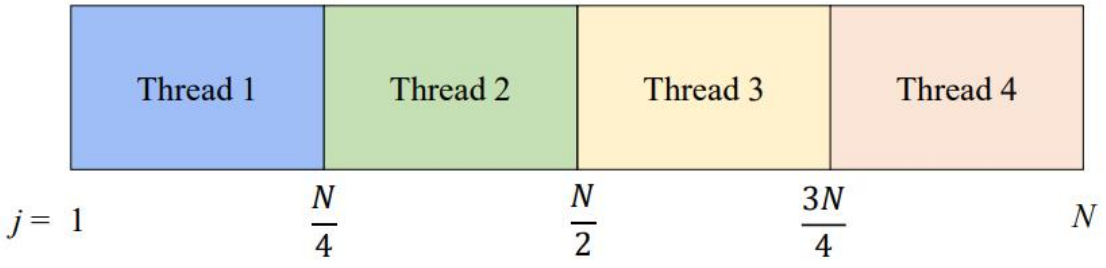
OpenMP: Scheduling omp for

How does a loop get split up ? *In **MPI**, we have to do it manually!!!*

If you do not tell what to do, the compiler decides
Usually compiler chooses "static" - chunks of N/p

```
#pragma omp parallel for default(shared) private(j)
  for (j=0; j<N; j++) {
         ... // some work here
}
```

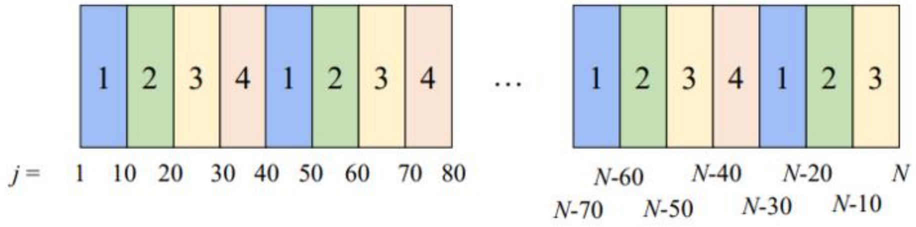
Unspecified schedule



OpenMP: Static Scheduling

You can tell the compiler what size chunks to take ?

```
#pragma omp parallel for default(shared) private(j) schedule(static,10)
  for (j=0; j<N; j++) {
        ... // some work here
}
```



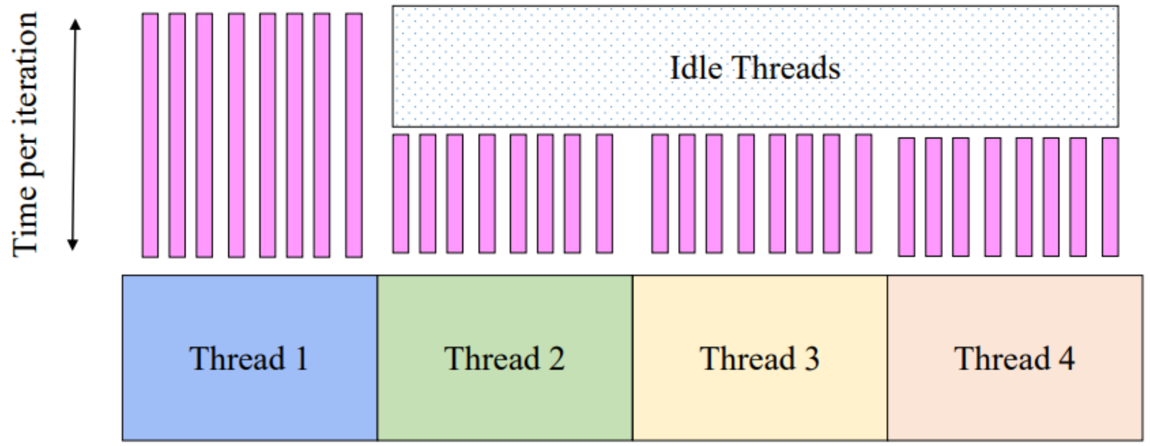
Keeps assigning chunks until done.

Chunk size that is not a multiple of the loop will results in thread with uneven numbers.

OpenMP: Problem with Static Scheduling

What happens if loop iterations do not take the same amount of time ?

Load imbalance



OpenMP: Dynamic Scheduling

Chunks are assigned on the fly, as threads become available.

When a thread finishes on chunk, it is assigned another

```
#pragma omp parallel for default(shared) private(j) schedule(dynamic,10)
  for (j=0; j<N; j++) {
        ... // some work here
}
```

Caveat: higher overhead than static!

OpenMP: For Scheduling Recap

```
#pragma omp parallel for schedule(type [,size])
```

Scheduling types

Static
- Chunks of specified size assigned round-robin

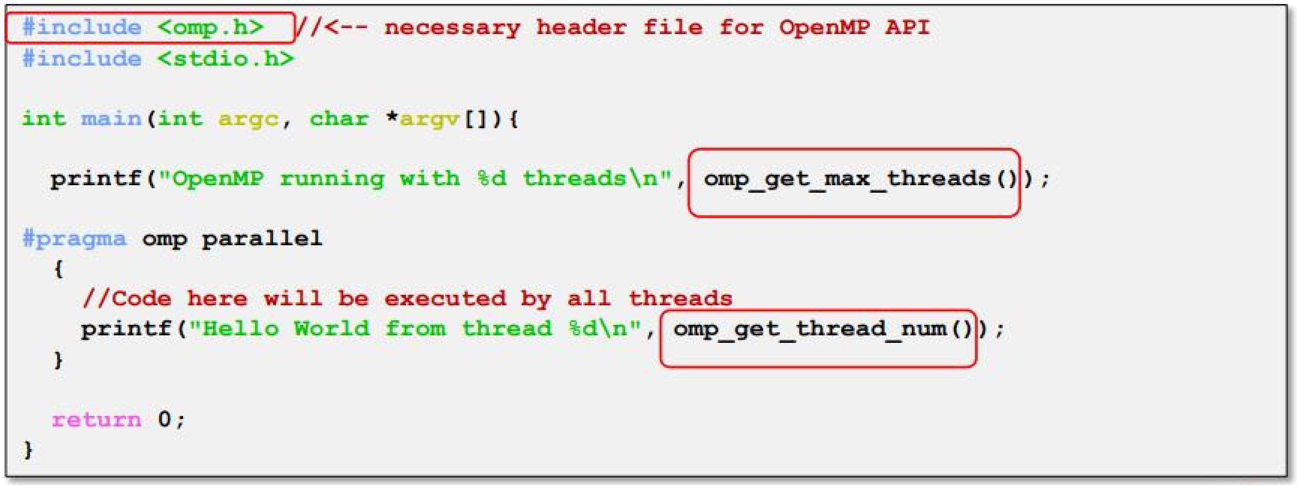
Dynamic
- Chunks of specified size are assigned when thread finishes previous chunk

Guided
- Like dynamic, but chunks are exponentially decreasing
- Chunk will not be smaller than specified size

Runtime
- Type and chunk determined at runtime via environment variables

OpenMP: API

- API for library calls that perform useful functions
- Must include "omp:h"
- Will not compile without OpenMP compiler support



```
#include <omp.h>  //<-- necessary header file for OpenMP API
#include <stdio.h>

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

  printf("OpenMP running with %d threads\n", omp_get_max_threads());

#pragma omp parallel
  {
    //Code here will be executed by all threads
    printf("Hello World from thread %d\n", omp_get_thread_num());
  }

  return 0;
}
```

OpenMP: API

```
void omp_set_num_threads(int num_threads)
```

Sets number of treads used in next parallel section
Overrides OMP_NUM_THREADS environment variable

```
int omp_get_max_threads()
```

Returns max possible (generally set by OMP_NUM_THREADS)

```
int omp_get_num_threads()
```

Returns number of threads currently in team

```
int omp_get_thread_num()
```

Returns thread id of calling thread
Between 0 and omp_get_num_threads-1

```
double omp_get_wtime()
```

Returns number of seconds since some point
Use inpais time=(t2-t1)

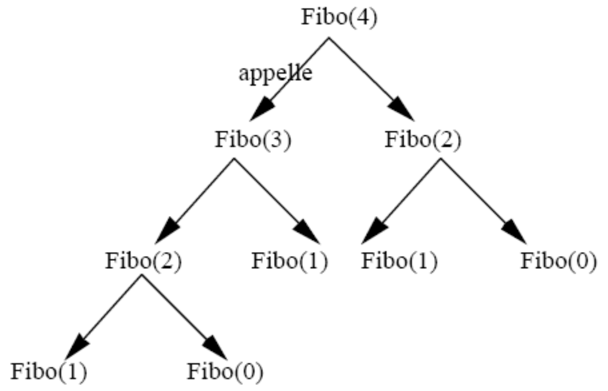
OpenMP: Example Fibonacci

```
int fib ( int n )
{
  int x,y;
  if ( n < 2 ) return n;
  #pragma omp task shared(x,n)
  x = fib(n-1);

  #pragma omp task shared(y,n)
  y = fib(n-2);

#pragma omp taskwait
return x+y;
}
```

```
int main()
{
#pragma omp parallel
  #pragma omp single nowait
  result = comp_fib_numbers(10);
return EXIT_SUCCESS;
}
```

fib(0) = 1
fib(1) = 1
fib(n) = fib(n-1) + fib(n-2)

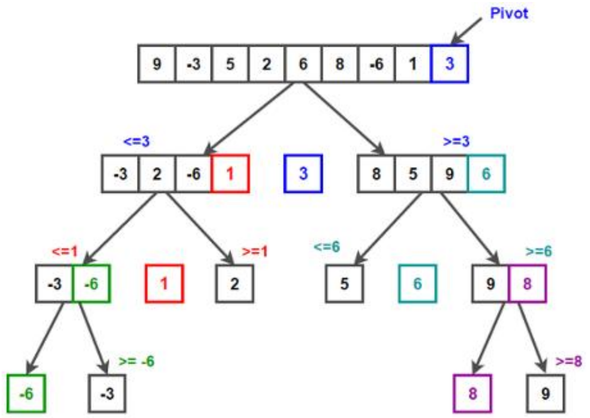
avec $n \in \mathbb{N}$



OpenMP: Example Quicksort

```
void quick_sort (int p, int r, float *data)
{
   if (p < r) {
       int q = partition (p, r, data);
        #pragma omp task

        quick_sort (p, q-1, data, low_limit);
        #pragma omp task
        quick_sort (q+1, r, data, low_limit); }
      }
   }
}
```

```
void par_quick_sort (int n, float *data)
{
   #pragma omp parallel
   {
      #pragma omp single nowait
      quick_sort (0, n, data);
   }
```

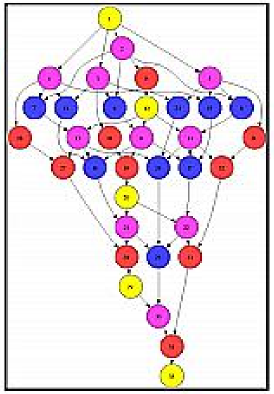


OpenMP: Example Cholesky Factorization

The **Cholesky factorization**, also known as Cholesky decomposition, is a process of breaking down of a Hermitian, positive-definite matrix into the product of a lower triangular matrix and its conjugate transpose, which is important for quick numerical solutions in linear algebra.

```
1: Input: Dictionary $\mathbf{D}$, signal $\underline{x}$, target sparsity $K$ *or* target error $\epsilon$
2: Output: Sparse representation $\underline{\gamma}$ such that $\underline{x} \approx \mathbf{D}\underline{\gamma}$
3: Init: Set $I := (\,)$, $\mathbf{L} := [1]$, $\underline{r} := \underline{x}$, $\underline{\gamma} := \underline{0}$, $\underline{\alpha} := \mathbf{D}^T\underline{x}$, $n := 1$
4: while (stopping criterion not met) do
5:     $\hat{k} := \underset{k}{\text{Argmax}}\ |\underline{d}_k^T\,\underline{r}\,|$
6:     if $n > 1$ then
7:         $\underline{w} :=$ Solve for $\underline{w}$ $\{\ \mathbf{L}\underline{w} = \mathbf{D}_I^T\underline{d}_{\hat{k}}\ \}$
8:         $\mathbf{L} := \begin{bmatrix} \mathbf{L} & \underline{0} \\ \underline{w}^T & \sqrt{1 - \underline{w}^T\underline{w}} \end{bmatrix}$
9:     end if
10:    $I := (\,I, \hat{k}\,)$
11:    $\underline{\gamma}_I :=$ Solve for $\underline{c}$ $\{\ \mathbf{L}\mathbf{L}^T\underline{c} = \underline{\alpha}_I\ \}$
12:    $\underline{r} := \underline{x} - \mathbf{D}_I\underline{\gamma}_I$
13:    $n := n + 1$
14: end while
```

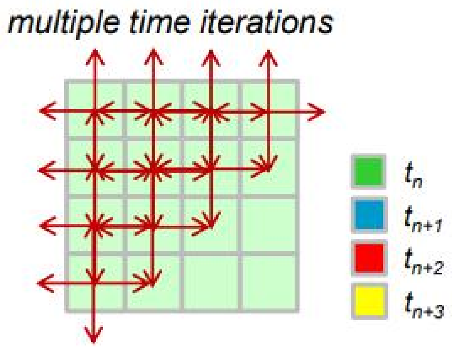
```
void cholesky(int ts, int nt, double* a[nt][nt]) {
  for (int k = 0; k < nt; k++) {
    // Diagonal Block factorization
    #pragma omp task depend(inout: a[k][k])
  ●potrf(a[k][k], ts, ts);

    // Triangular systems
    for (int i = k + 1; i < nt; i++) {
      #pragma omp task depend(in: a[k][k])
                  depend(inout: a[k][i])
    ●trsm(a[k][k], a[k][i], ts, ts);
    }

    // Update trailing matrix
    for (int i = k + 1; i < nt; i++) {
      for (int j = k + 1; j < i; j++) {
        #pragma omp task depend(inout: a[j][i])
                    depend(in: a[k][i], a[k][j])
      ●dgemm(a[k][i], a[k][j], a[j][i], ts, ts);
      }
      #pragma omp task depend(inout: a[i][i])
                  depend(in: a[k][i])
    ●syrk(a[k][i], a[i][i], ts, ts);
    }
  }
}
```



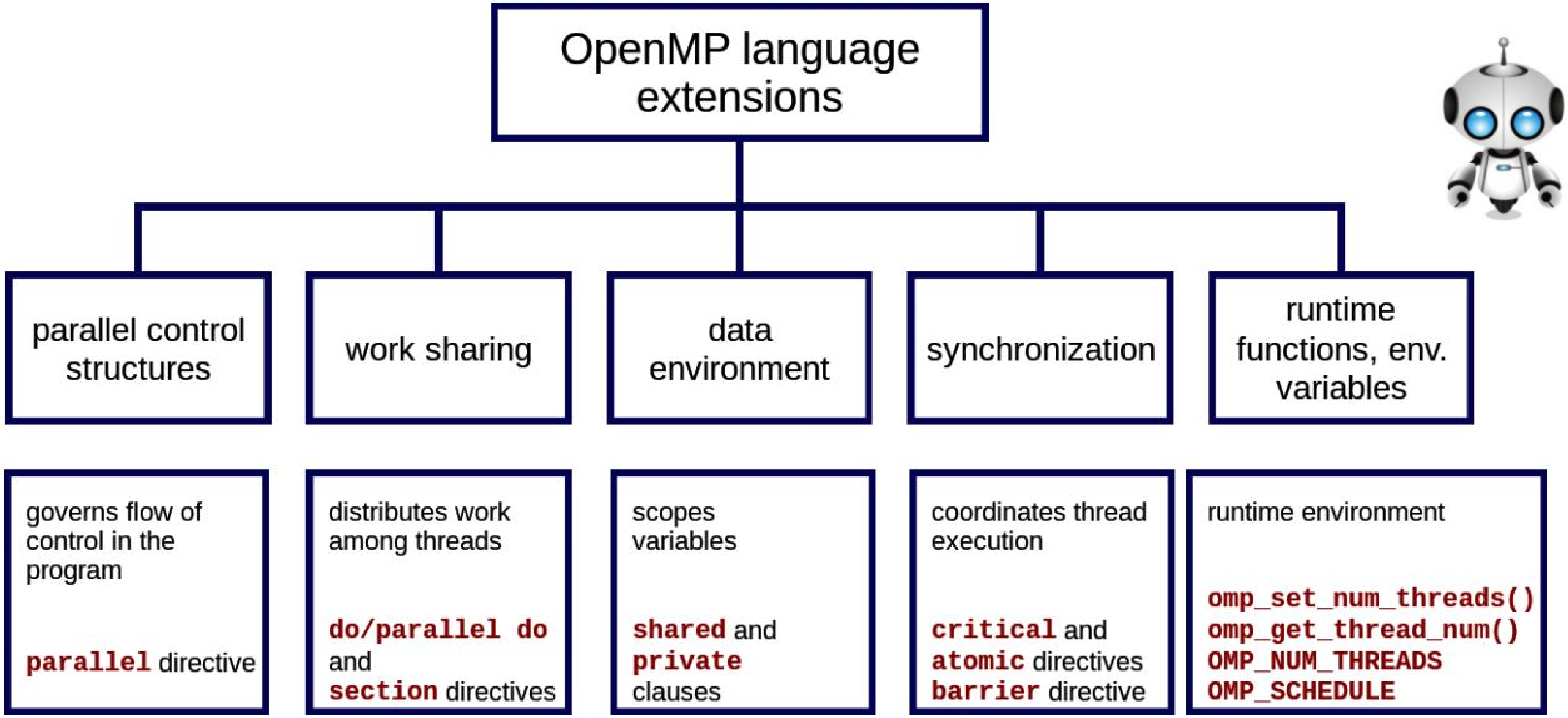
OpenMP: Example Gauss-Seidel

```
void gauss_seidel(int tsteps, int size, int TS, int (*p)[size]) {
  int NB = size / TS;

  #pragma omp parallel
  #pragma omp single
  for (int t = 0; t < tsteps; ++t)
    for (int ii=1; ii < size-1; ii+=TS)
      for (int jj=1; jj < size-1; jj+=TS) {
        #pragma omp task depend(inout: p[ii:TS][jj:TS])
            depend(in: p[ii-TS:TS][jj:TS], p[ii+TS:TS][jj:TS],
                        p[ii:TS][jj-TS:TS], p[ii:TS][jj:TS])
        {
          for (int i=ii; i<(1+ii)*TS; ++i)
            for (int j=jj; j<(1+jj)*TS; ++j)
               p[i][j] = 0.25 * (p[i][j-1] * p[i][j+1] *
                                  p[i-1][j] * p[i+1][j]);
        }
      }
}
```

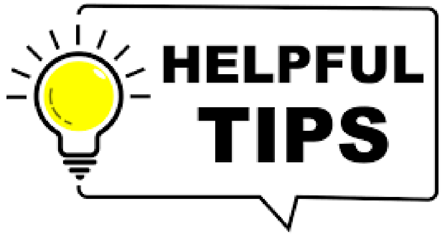
Gauss-Seidel Method is used to solve the linear system Equations. It is a method of iteration for solving n linear equation Ax=b with the unknown variables.



OpenMP: Summary Overview


OpenMP language extensions
parallel control structures
work sharing
data environment
synchronization
runtime functions, env. variables
governs flow of control in the program
parallel directive
distributes work among threads
do/parallel do and section directives
scopes variables
shared and private clauses
coordinates thread execution
critical and atomic directives barrier directive
runtime environment
omp_set_num_threads()
omp_get_thread_num()
OMP_NUM_THREADS
OMP_SCHEDULE

OpenMP: Performance Tips...



- Avoid serialization !
- Avoid using **#pragma omp parallel** for before loop
  - Cane have significant overhead
    - -Thread creation and scheduling is not free!!
  - Try for broader parallelism
    - -One **#pragma omp parallel**, multiple **#pragma omp for**
  - Always try to parallelize the other most loop
- Use reduction whenever possible
- Minimize I/O
- Minimize critical
  - Use **atomic** instead of critical where possible

Thank you for your attention !