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Introduction to OpenMP

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Outline

- Brief overview of parallel computing and OpenMP
- OpenMP Programming
  - Parallel constructs
  - Work-sharing constructs
  - Data clauses
  - Data race condition
  - Synchronization constructs
  - More clauses

Parallel Computing

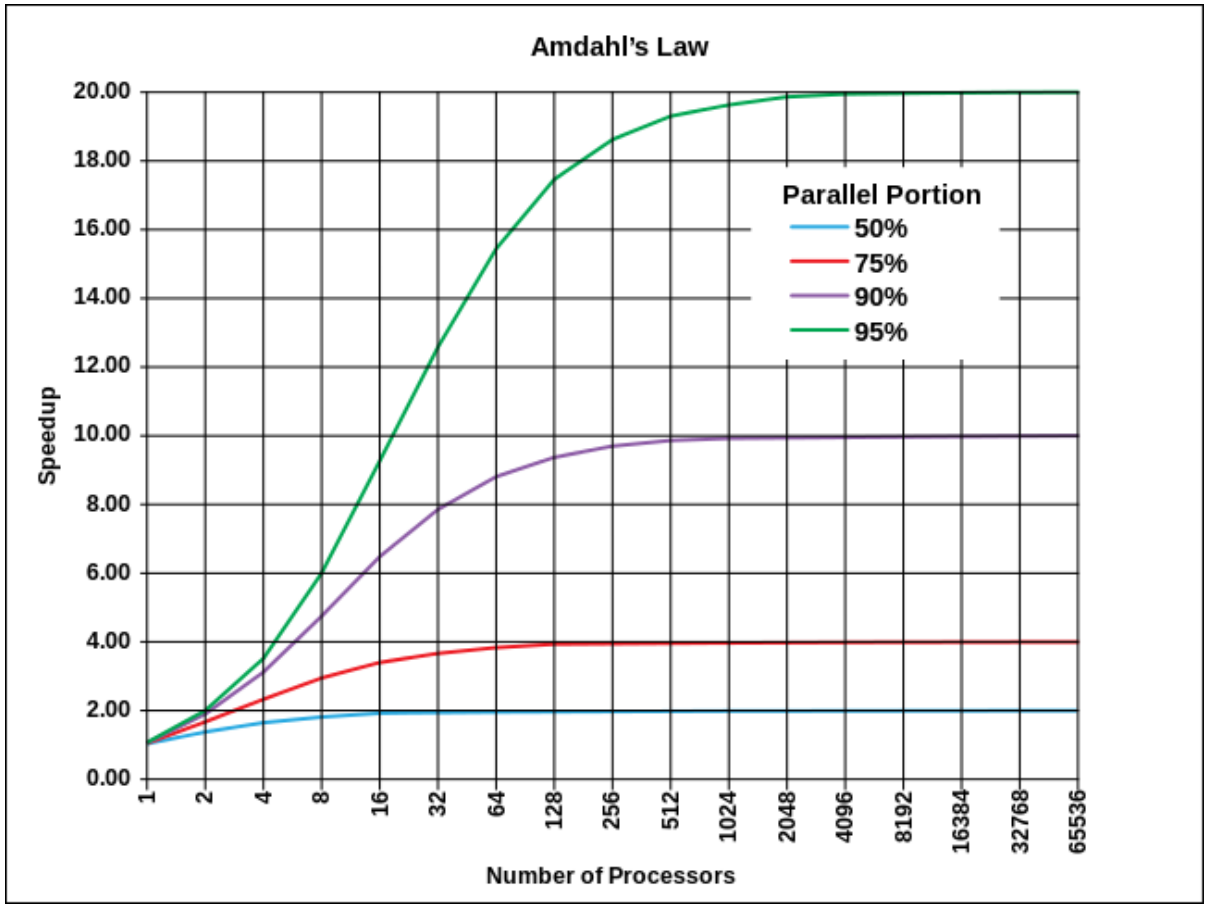
- Parallel computing is a type of computation in which many calculations are carried out simultaneously.

- Speedup of a parallel program,

$$S(p) = {T(1)}/{T(p)} = \frac{1}{\alpha + {1}/{p}\,(1-\alpha)}$$

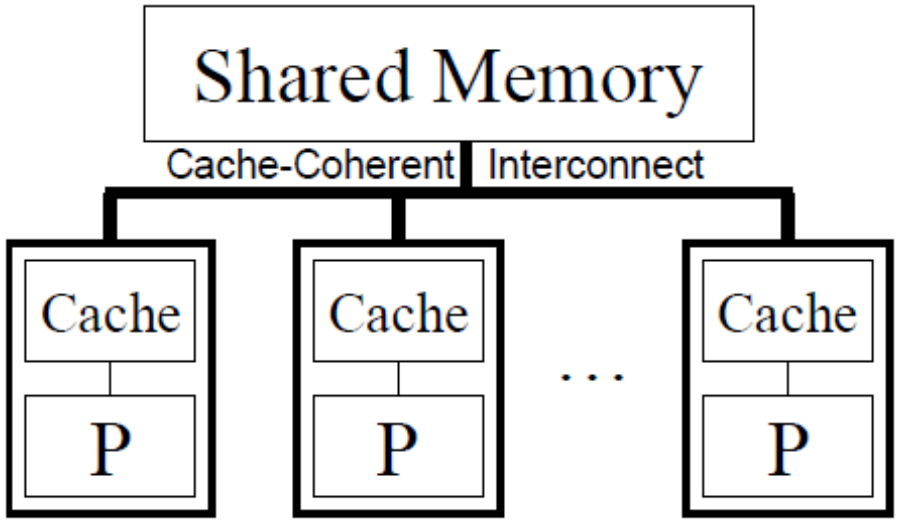
p: number of processors (or cores),

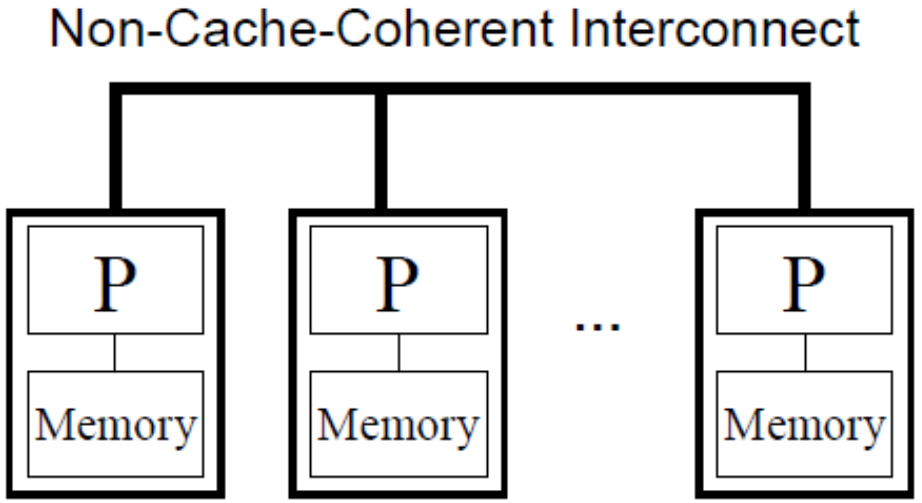
α: fraction of the program that is serial.



- Figure from: https://en.wikipedia.org/wiki/Parallel_computing

Two types of parallel parallelism





- Shared memory system
- For example, a single node on a cluster
- Open Multi-processing (OpenMP)

- Distributed memory system
- For example, mutli nodes on a cluster
- Message Passing Interface (MPI)

✓ Figures from the book *Using OpenMP: Portable Shared Memory Parallel Programming*

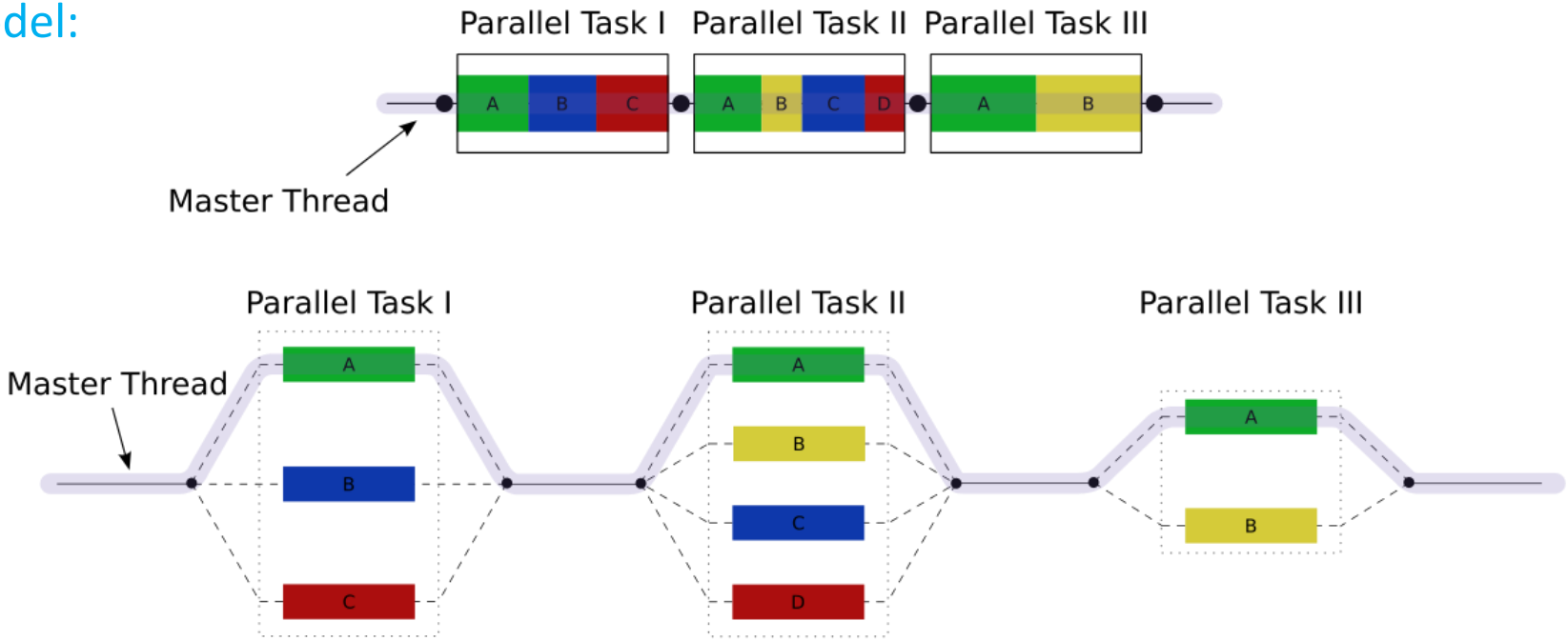
OpenMP

- OpenMP (Open Multi-Processing) is an API (application programming interface) that supports multi-platform shared memory multiprocessing programming.
- Supporting languages: C, C++, and Fortran.
- Consists of a set of compiler directives, library routines, and environment variables that influence run-time behavior.
- OpenMP 4.0 supports accelerators.

Parallelism of OpenMP

- Multithreading: a master thread forks a specified number of slave threads and the system divides a task among them. The threads then run concurrently, with the runtime environment allocating threads to different processors (or cores).

- Fork-join model:



- Figure from: http://en.wikipedia.org/wiki/OpenMP

The first OpenMP program: Hello world!

- Hello world in C language

```
#include <omp.h>
int main() {
int id;
#pragma omp parallel private(id)
{
   id = omp_get_thread_num();
   if (id%2==1)
     printf("Hello world from thread %d, I am odd\n", id);
   else
     printf("Hello world from thread %d, I am even\n", id);
  }
}
```

- Hello world in Fortran language

```
program hello
   use omp_lib
   implicit none
   integer i
   !$omp parallel private(i)
   i = omp_get_thread_num()
   if (mod(i,2).eq.1) then
      print *,'Hello from thread',i,', I am odd!'
   else
      print *,'Hello from thread',i,', I am even!'
   endif
   !$omp end parallel
end program hello
```

OpenMP directive syntax

- In C/C++ programs

#pragma omp *directive-name [clause[[,] clause]. . .]*

- In Fortran programs

!$omp *directive-name [clause[[,] clause]. . .]*

- Directive-name is a specific keyword, for example *parallel*, that defines and controls the action(s) taken.
- Clauses, for example *private*, can be used to further specify the behavior.

Compile and run OpenMP programs

Compile C/C++/Fortran codes

> icc/icpc/ifort -openmp name.c/name.f90 -o name

> gcc/g++/gfortran -fopenmp name.c/name.f90 -o name

> pgcc/pgc++/pgf90 -mp name.c/name.f90 -o name

Run OpenMP programs

> export OMP_NUM_THREADS=4 # set number of threads

> ./name

> time ./name # run and measure the time.

OpenMP programming

- Parallel Construct
- Work-Sharing Constructs

  Loop Construct

  Sections Construct

  Single Construct

  Workshare Construct (Fortran only)
- Data clauses

  shared, private, lastprivate, firstprivate, default
- Synchronization constructs

  Barrier Construct

  Critical Construct

  Atomic Construct
- More clauses:

  reduction, num_thread, schedule

- Construct : An OpenMP executable directive and the associated statement, loop, or structured block, not including the code in any called routines.

Parallel construct

- Syntax in C/C++ programs

```
#pragma omp parallel [clause[[,] clause]. . . ]
    …… code block ……
```

- Syntax in Fortran programs

```
!$omp parallel [clause[[,] clause]. . . ]
    …… code block ……
!$omp end parallel
```

- Parallel construct is used to specify the computations that should be executed in parallel.
- A team of threads is created to execute the associated parallel region.
- The work of the region is replicated for every thread.
- At the end of a parallel region, there is an implied barrier that forces all threads to wait until the computation inside the region has been completed.

Work-sharing constructs

Functionality	Syntax in C/C++	Syntax in Fortran
Distribute iterations	**#pragma omp for**	**!$omp do**
Distribute independent works	**#pragma omp sections**	**!$omp sections**
Use only one thread	**#pragma omp single**	**!$omp single**
Parallelize array syntax	**N/A**	**!$omp workshare**

- Many applications can be parallelized by using just a parallel region and one or more of work-sharing constructs, possibly with clauses.

- The parallel and work-sharing (except single) constructs can be combined.
- Following is the syntax for combined parallel and work-sharing constructs,

Combine parallel construct with …	Syntax in C/C++	Syntax in Fortran
Loop construct	**#pragma omp parallel for**	**!$omp parallel do**
Sections construct	**#pragma omp parallel sections**	**!$omp parallel sections**
Workshare construct	**N/A**	**!$omp parallel workshare**

Loop construct

- The loop construct causes the iterations of the loop immediately following it to be executed in parallel.

- Syntax in C/C++ programs

```
#pragma omp for [clause[[,] clause]. . . ]
    …… for loop ……
```

- Syntax in Fortran programs

```
!$omp do [clause[[,] clause]. . . ]
    …… do loop ……
[!$omp end do]
```

- The terminating **!$omp end do** directive in Fortran is optional but recommended.

- Distribute iterations in a parallel region

```
#pragma omp parallel for shared(n,a) private(i)
   for (i=0; i<n; i++)
         a[i] = i + n;
```

- shared clause: All threads can read from and write to a shared variable.
- private clause: Each thread has a local copy of a private variable.
- The maximum iteration number *n* is shared, while the iteration number *i* is private.
- Each thread executes a subset of the total iteration space i = 0, . . . , n − 1
- The mapping between iterations and threads can be controlled by the schedule clause.

- Two work-sharing loops in one parallel region

```
#pragma omp parallel shared(n,a,b) private(i)
{
   #pragma omp for
   for (i=0; i<n; i++)   a[i] = i+1;
   //  there is an implied barrier

   #pragma omp for
   for (i=0; i<n; i++)   b[i] = 2 * a[i];
}     /*-- End of parallel region --*/
```

- The distribution of iterations to threads could be different for the two loops.
- The implied barrier at the end of the first loop ensures that all the values of a[i] are updated before they are used in the second loop.

Exercise 1

- SAXPY in OpenMP:

The SAXPY program is to add a scalar multiple of a real vector to another real vector:

s = a*x + y.

1. Provided a serial SAXPY code, parallelize it using OpenMP directives.
2. Compare the performance between serial and OpenMP codes.

Sections construct

- Syntax in C/C++ programs

```
#pragma omp sections [clause[[,] clause]. . . ]
{
[#pragma omp section ]
…… code block 1 ……
[#pragma omp section
…… code block 2 ……  ]
. . .
}
```

- Syntax in Fortran programs

```
!$omp sections [clause[[,] clause]. . . ]
[!$omp section ]
…… code block 1 ……
[!$omp section
…… code block 2 ……  ]
. . .
!$omp end sections
```

- The work in each section must be independent.
- Each section is distributed to one thread.

- Example of parallel sections

```
#pragma omp parallel sections
{
    #pragma omp section
    funcA();
     #pragma omp section
    funcB();
}  /*-- End of parallel region --*/
```

- The most common use of the sections construct is probably to execute function or subroutine calls in parallel.

- There is a load-balancing problem, if the amount of work in different sections are not equal.

Single construct

- Syntax in C/C++ programs

```
#pragma omp single [clause[[,] clause]. .
.
…… code block  ……
```

- Syntax in Fortran programs

```
!$omp single [clause[[,] clause]. . . ]
…… code block  ……
!$omp end single
```

- The code block following the single construct is executed by one thread only.
- The executing thread could be any thread (not necessary the master one).
- The other threads wait at a barrier until the executing thread has completed.

- An example of the single construct

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

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

- Only one thread initializes the shared variable a.
- If the single construct is omitted here, multiple threads could assign the value to *a* at the same time, potentially resulting in a memory problem.
- The implicit barrier at the end of the single construct ensures that the correct value is assigned to the variable a before it is used by all threads.

Workshare construct

- Workshare construct is only available for Fortran.

- Syntax in Fortran programs

```
!$omp workshare [clause[[,] clause]. . . ]
…… code block  ……
!$omp end workshare
```

- It is used to parallelize Fortran array operations.

- An example of workshare construct

```
!$OMP PARALLEL SHARED(n,a,b,c)
!$OMP WORKSHARE
    b(1:n) = b(1:n) + 1
    c(1:n) = c(1:n) + 2
    a(1:n) = b(1:n) + c(1:n)
!$OMP END WORKSHARE
!$OMP END PARALLEL
```

- These array operations are parallelized.

- The OpenMP compiler must generate code such that the updates of *b* and *c* have completed before a is computed.

Lastprivate clause

- private clause: The values of data can no longer be accessed after the region terminates.
- lastprivate clause: The sequentially last value is accessible outside the region.
- For loop construct, “last” means the iteration of the loop that would be last in a sequential execution.
- For sections construct, “last” means the lexically last sections construct.
- Lastprivate clause is not available for parallel construct, since “last” can not be defined.

```
#pragma omp parallel for private(i) lastprivate(a)
for (i=0; i<n; i++) {
      a = i+1;
      printf("Thread %d has a value of a = %d for i = %d\n", omp_get_thread_num(),a,i);
}    /*-- End of parallel for --*/
printf(“After parallel for: i = %d , a = %d\n", i, a);
```

- Alternative code with shared clause

```
#pragma omp parallel for private(i, a) shared(a_shared)
for (i=0; i<n; i++) {
    a = i+1;
    if ( i == n-1 ) a_shared = a;
}   /*-- End of parallel for --*/
```

- All behavior of the lastprivate clause can be reproduced by the shared clause, but the lastprivate clause is more recommended.

- The use of lastprivate results in a performance penalty, because the OpenMP library needs to keep track of which thread executes the last iteration.

Firstprivate clause

- private clause: Preinitialized value of variables are not passed to the parallel region.
- firstprivate clause: Each thread has a preinitialized copy of the variable. This variable is still private, so threads can update it individually.
- Firstprivate clause is available for parallel, loop, sections and single constructs.

```
int i, vtest=10, n=20;
#pragma omp parallel for private(i) firstprivate(vtest) shared(n)
for(i=0; i<n; i++) {
        printf("thread %d: initial value = %d\n", omp_get_thread_num(), vtest);
        vtest=i;
}
printf("value after loop = %d\n", vtest);
```

Default clause

- The default clause is used to give variables a default data-sharing attribute.
- It is applicable to the parallel construct only.

- Syntax in C programs

```
default (none | shared)
```

- Syntax in Fortran programs

```
default (none | shared | private)
```

- An example: declares all variables to be shared, with the some exceptions.

```
#pragma omp parallel for default(shared) private(a,b,c)
```

- If default(none) is specified, the programmer is forced to specify a data-sharing attribute for each variable in the construct.

Barrier construct

- Threads wait for each other at a barrier.
- No thread may proceed beyond a barrier until all threads in the team have reached the barrier.

- Syntax in C/C++ programs

```
#pragma omp barrier
```

- Syntax in Fortran programs

```
!$omp barrier
```

Two important restrictions apply to the barrier construct:

- Each barrier must be encountered by all threads in a team, or by none at all.
- The sequence of work-sharing regions and barrier regions encountered must be the same for every thread in the team.

- An example: Illegal use of the barrier
- The barrier is not encountered by all threads in the team, and therefore this is not illegal.

```
#pragma omp parallel
{
   if ( omp_get_thread_num() == 0 ){
      .....
      #pragma omp barrier  // Correction: the barrier should be out of the if-else region
   }
   else{
      .....
      #pragma omp barrier
   }
  //  #pragma omp barrier   // The barrier should be added here.
}  /*-- End of parallel region --*/
```

- Also, a barrier should not be in a work-sharing construct, a critical section, or a master construct.

- A dead lock situation

```
work1(){
   /*-- Some work performed here --*/
   #pragma omp barrier   // Correction: remove this barrier
}
work2(){
   /*-- Some work performed here --*/
}

main(){
   #pragma omp parallel sections
   {
      #pragma omp section
      work1();
      #pragma omp section
      work2();
   }   // An implicit barrier
}
```

- If executed by two threads, this program never finishes.
- Thread1 executing work1 waits forever in the explicit barrier, which thread2 will never encounter.
- Thread2 executing work2 waits forever in the implicit barrier at the end of the *parallel sections* construct, which thread1 will never encounter.
- Note: Do not insert a barrier that is not encountered by all threads of the same team.

Master construct

- The master construct defines a block of code that is guaranteed to be executed by the master thread only.
- It does not have an implied barrier on entry or exit. In the cases where a barrier is not required, the master construct may be preferable compared to the single construct.

- Syntax in C/C++ programs

```
#pragma omp master
…… code block …..
```

- Syntax in Fortran programs

```
!$omp master
…… code block …..
!$omp end master
```

- The master construct is often used (in combination with barrier construct) to initialize data.

- An example: Incorrect use of master construct
- This code fragment implicitly assumes that variable *Xinit* is available to all threads after it is initialized by the master thread. This is incorrect. The master thread might not have executed the assignment when another thread reaches it.

```
int Xinit, Xlocal;
#pragma omp parallel shared(Xinit) private(Xlocal)
{
    #pragma omp master // correct version 1: use single construct instead, #pragma omp single
    {
        Xinit = 10;
    }
    // correct version 2: insert a barrier here, #pragma omp barrier
    Xlocal = Xinit;    /*-- Xinit might not be available for other threads yet --*/
}    /*-- End of parallel region --*/
```

Data race condition

- Data race conditions arise when multithreads read or write the same shared data simultaneously.
- Example: two threads each increases the value of a shared integer variable by one.

Correct sequence

Thread 1	Thread 2		value
			0
read value		←	0
Increase value			0
write back		→	1
	read value	←	1
	increase value		1
	write back	→	2

Incorrect sequence

Thread 1	Thread 2		value
			0
read value		←	0
	read value	←	0
increase value			0
	increase value		0
write back		→	1
	write back	→	1

- Example of data racing: sums up elements of a vector

Different threads read and write the shared data sum simultaneously.

A data race condition arises!

The final result of *sum* could be incorrect!

```
sum = 0;
 #pragma omp parallel for shared(sum,a,n) private(i)
  for (i=0; i<n; i++)
  {
     sum = sum + a[i];
  }  /*-- End of parallel for --*/
printf("Value of sum after parallel region: %f\n",sum);
```

Atomic construct

- The atomic construct allows multiple threads to safely update a shared variable.
- The memory update (such as write) in the next instruction will be performed atomically. It does not make the entire statement atomic. Only the memory update is atomic.
- It is applied only to the (single) assignment statement that immediately follows it.

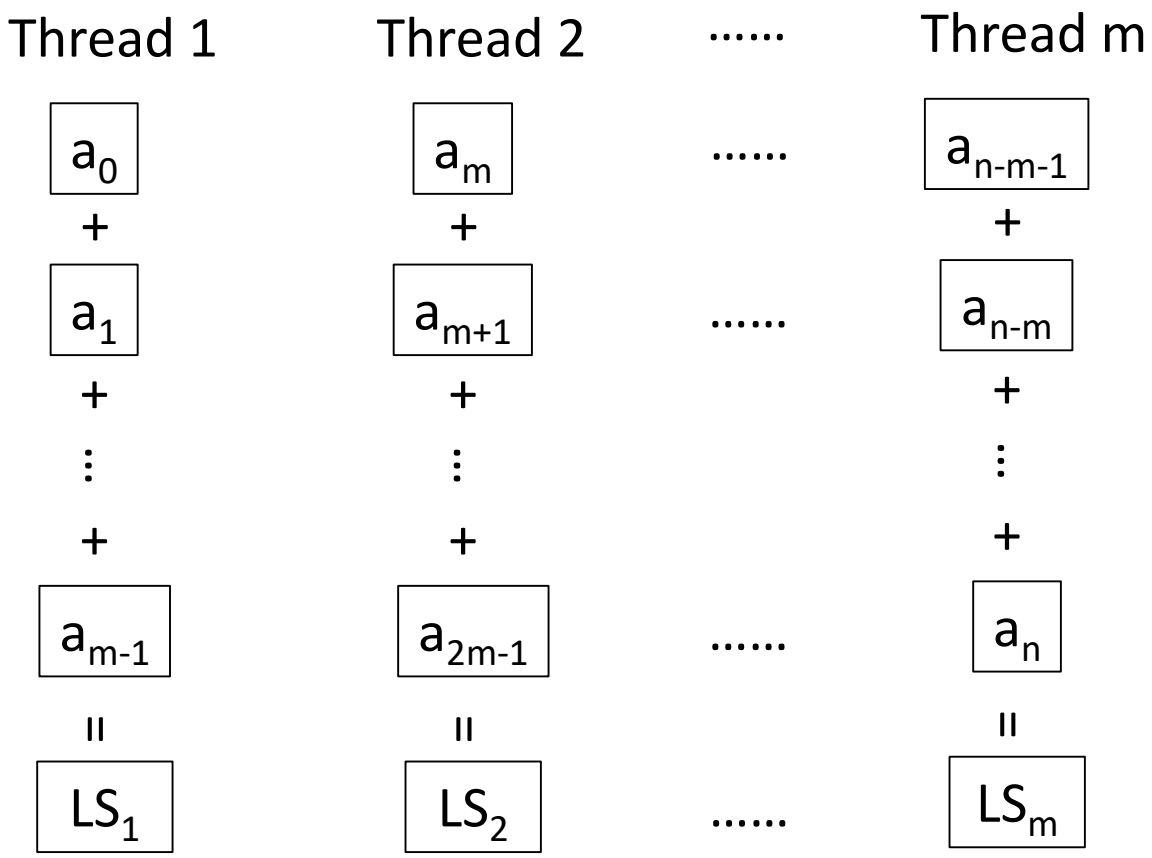
	C/C++ programs	Fortran programs
• Syntax	**#pragma omp atomic** …… a single statement …..	**!$omp atomic** …… a single statement ….. **!$omp end atomic**
• Supported operators	+, *, -, /, &, ^, |, <<, >>.	+, *, -, /, .AND., .OR., .EQV., .NEQV. .

- The first try to solve the data-race problem: use *atomic* (correct but slow)
- The atomic construct avoids the data racing condition. Therefore the result is correct.
- But all elements are added sequentially, and there is performance penalty for using *atomic*, because the system coordinates all threads.
- This code is even slower than a serial code!

```
sum = 0;
 #pragma omp parallel for shared(n,a,sum) private(i) // Optimization: use reduction instead of atomic
 for (i=0; i<n; i++)
 {
       #pragma omp atomic
        sum += a[i];
 }   /*-- End of parallel for --*/
printf("Value of sum after parallel region: %d\n",sum);
```

- A partially parallel scheme to avoid data race

Step 1: Calculate local sums in parallel



m: number of threads

n: array length

LS: local sum

Step 2: Update total sum sequentially

Thread 1	Thread 2	……	Thread m
Read initial S			
$S = S + LS_1$			
Write S			
	Read S		
	$S = S + LS_2$		
	Write S		
		……	
			Read S
			$S = S + LS_m$
			Write S

m: number of threads

LS: local sum

S: total sum

- The second try to solve the data-race problem: use *atomic* (correct and fast)

- Each thread adds up its local sum.
- The *atomic* is only applied for adding up local sums to obtain the total sum.

```
sum = 0;
#pragma omp parallel shared(n,a,sum) private(sumLocal)
{
    sumLocal = 0;
    #pragma omp for
    for (i=0; i<n; i++)  sumLocal += a[i];
    #pragma omp atomic
    sum += sumLocal;
}  /*-- End of parallel region --*/
printf("Value of sum after parallel region: %d\n",sum);
```

Critical construct

- The critical construct provides a means to ensure that multiple threads do not attempt to update the same shared data simultaneously.
- The enclosed code block will be executed by only one thread at a time.
- When a thread encounters a critical construct, it waits until no other thread is executing a critical region with the same name.

- Syntax in C/C++ programs

```
#pragma omp critical [(name)]
…… code block …..
```

- Syntax in Fortran programs

```
!$omp critical [(name)]
…… code block …..
!$omp end critical [(name)]
```

- The third try to solve the data-race problem: use *critical* (correct and fast)
- Each thread adds up its local sum.
- The critical region is used to avoid a data race condition when updating the total sum.

```
sum = 0;
#pragma omp parallel shared(n,a,sum) private(sumLocal)
{
    sumLocal = 0;
    #pragma omp for
    for (i=0; i<n; i++)  sumLocal += a[i];
    #pragma omp critical (update_sum)
    {
        sum += sumLocal;
        printf("TID=%d: sumLocal=%d sum = %d\n", omp_get_thread_num(), sumLocal, sum);
    }
}  /*-- End of parallel region --*/
printf("Value of sum after parallel region: %d\n",sum);
```

- Another example of critical construct: avoid garbled output

A critical region helps to avoid intermingled output when multiple threads print from within a parallel region.

```
#pragma omp parallel private(TID)
{
  TID = omp_get_thread_num();
  #pragma omp critical (print_tid)
  {
       printf("Thread %d : Hello, ",TID);
       printf(“world!\n");
  }
} /*-- End of parallel region --*/
```

Reduction clause

- The fourth try to solve the data-race problem: use *reduction* (correct, fast and simple)

```
#pragma omp parallel for default(none) shared(n,a) private(i) reduction(+:sum)
 for (i=0; i<n; i++)
       sum += a[i];
 /*-- End of parallel reduction --*/
```

- The reduction variable is protected to avoid data race.
- The partially parallel scheme mentioned before is applied behind the scene.
- An OpenMP compiler will generate a roughly identical machine code for using reduction clause (the code in this page) and for using critical construct (the code in a previous page).
- The reduction variable is shared by default and it is not necessary to specify it explicitly as “shared”.

- Operators and statements supported by the reduction clause

	C/C++	Fortran
Typical statements	x = x *op* expr x *binop* = expr x = expr *op* x (except for subtraction) x++ ++x x-- --x	x = x *op* expr x = expr *op* x (except for subtraction) x = *intrinsic* (x, expr_list) x = *intrinsic* (expr_list, x)
op could be	+, *, -, &, ^, |, &&, or ||	+, *, -, .and., .or., .eqv., or .neqv.
binop could be	+, *, -, &, ^, or |	N/A
Intrinsic function could be	N/A	max, min, iand, ior, ieor

Exercise 2

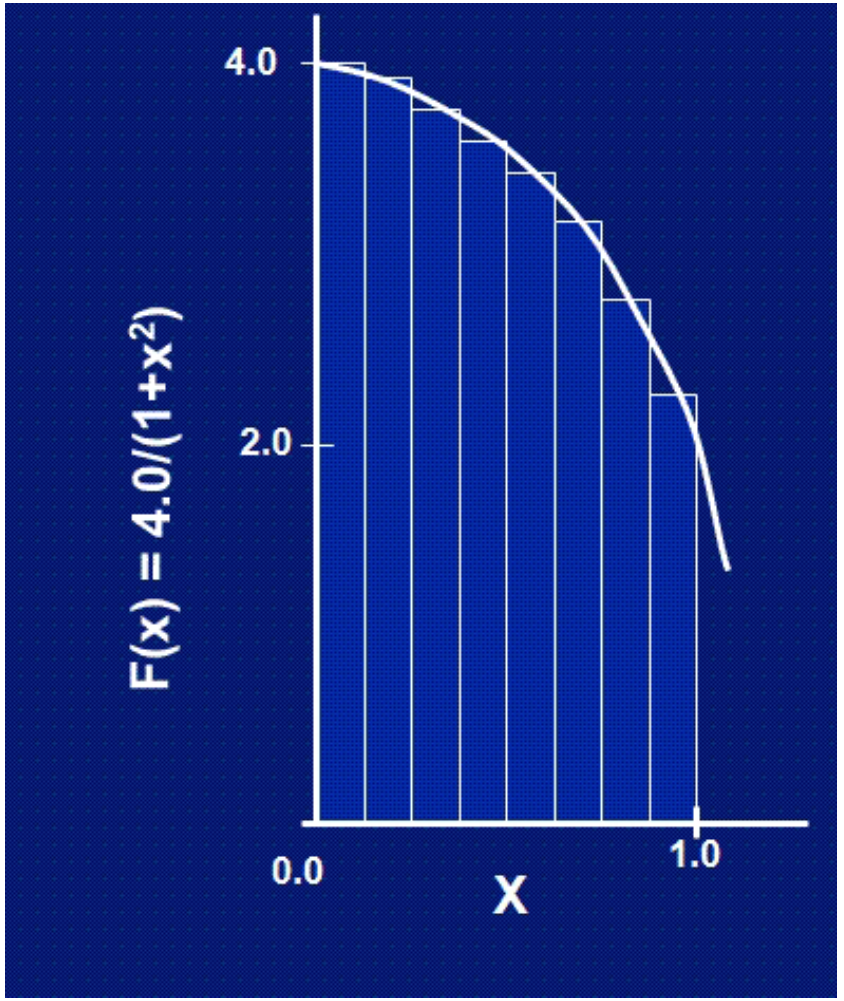
- Compute the value of pi:

$$\int_0^1 \frac{4.0}{(1+x^2)}\,dx = \pi$$

The integration can be numerically approximated as the sum of a number of rectangles.

$$\sum_{i=0}^{N} F(x_i)\Delta x \approx \pi$$

1. Provided the serial code for computing the value of pi, parallelize it using OpenMP directives.
2. Compare the performance between seral and OpenMP codes.



Num_threads clause

- It is supported on the parallel construct only and
- It is used to specify the number of threads in the parallel region.

```
omp_set_num_threads(4);
#pragma omp parallel if (n > 5) num_threads(n) default(none) shared(n)
{
   #pragma omp single
   {
      printf("Number of threads in parallel region: %d\n", omp_get_num_threads());
   }
   printf("Print statement executed by thread %d\n", omp_get_thread_num());
} /*-- End of parallel region --*/
```

Schedule clause

- Specifies how iterations of the loop are assigned to the threads in the team.
- Supported on the loop construct only.
- The iteration space is divided into chunks. A chunk is a contiguous nonempty subset of the iteration space. It represents the granularity of workload distribution.

- Syntax **schedule(kind [,chunk_size])**

- The static schedule works best for regular workloads. It is the default schedule on many OpenMP compilers.
- The dynamic and guided schedules are useful for handling poorly balanced and unpredictable workloads. There is a performance penalty for using dynamic or guided schedules.

- Schedule type

type	description
static	The chunks are assigned to the threads statically in a round-robin manner, in the order of the thread number.
dynamic	The chunks are assigned to threads as the threads request them. When a thread finishes, it will be assigned the next chunk that hasn’t been executed yet.
guided	Similar to the dynamic schedule, except that the chunk size changes at run time. It begins with big chunks, but then adjusts to smaller chunk sizes if the workload is imbalanced.
runtime	The schedule and (optional) chunk size are set through the OMP_SCHEDULE environment variable.

- An example of schedule clause:

In this code, the workload in the inner loop depends on the value of the outer loop iteration variable i. Therefore, the workload is not balanced, and the static schedule is not the best choice. Dynamic or guided schedules are required.

```
#pragma omp parallel for default(none) schedule(runtime) private(i,j) shared(n)
for (i=0; i<n; i++)
{
   printf("Iteration %d executed by thread %d\n", i, omp_get_thread_num());
   for (j=0; j<i; j++)
        system("sleep 1");
}
```

Appendix A: OpenMP built-in functions

- Enable the usage of OpenMP functions:

C/C++ program: include omp.h .

Fortran program: include omp_lib.h or use omp_lib module.

- List of OpenMP functions:

omp_set_num_threads(integer) : set the number of threads

omp_get_num_threads(): returns the number of threads

omp_get_thread_num(): returns the number of the calling thread.

omp_set_dynamic(integer|logical): dynamically adjust the number of threads

omp_get_num_procs(): returns the total number of available processors when it is called.

omp_in_parallel(): returns true if it is called within an active parallel region. False otherwise.

Appendix B: OpenMP runtime variables

OMP_NUM_THREADS : the number of threads (=integer)

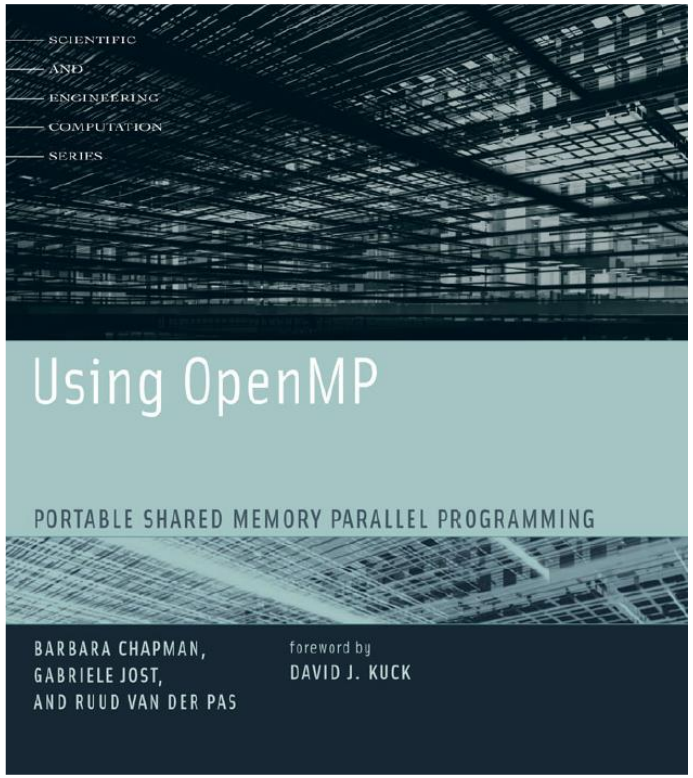
OMP_SCHEDULE : the schedule type (=kind,chunk . Kind could be static, dynamic or guided)

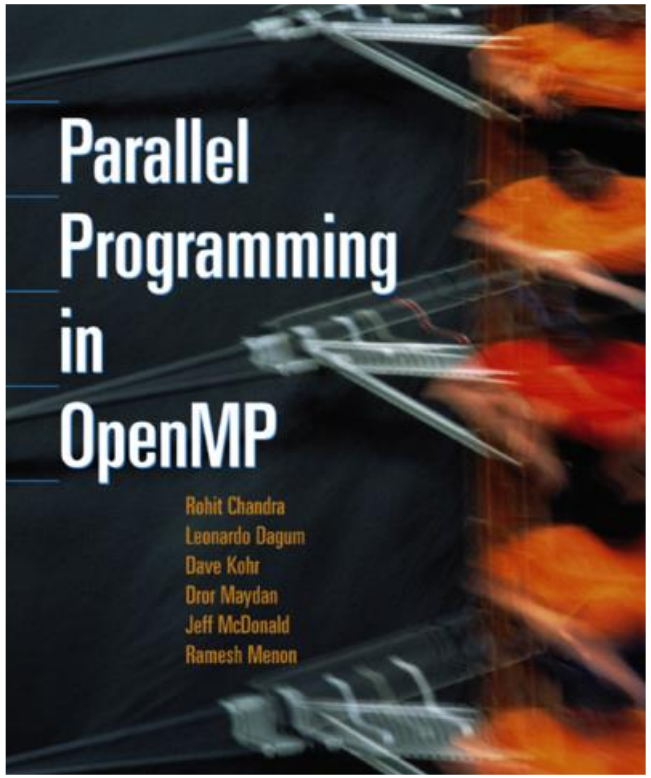
OMP_DYNAMIC : dynamically adjust the number of threads (=true | =false).

KMP_AFFINITY : only for intel compiler, to bind OpenMP threads to physical processing units.
(=compact | =scatter | =balanced).
Example usage: export KMP_AFFINITY= compact,granularity=fine,verbose .

Further information

❑References





❑Help

help@scc.bu.edu
shaohao@bu.edu

❑ OpenMP official website: http://openmp.org/wp/