OpenMP
Shared-Memory Parallel Programming

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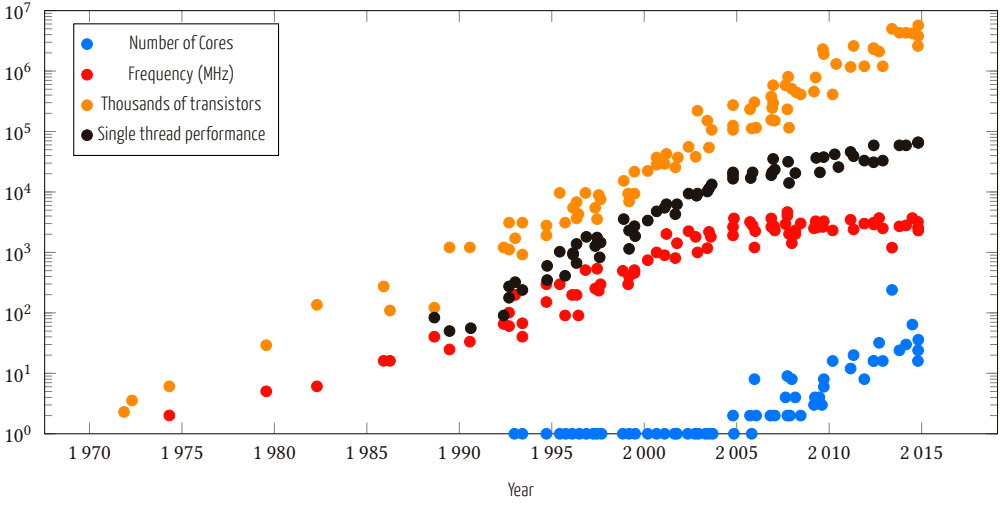
Motivations for Parallel Computing



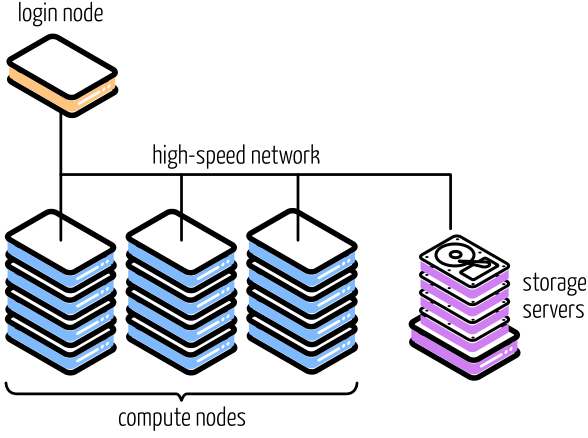
Motivations for Parallel Computing

- In the years 2000's the CPU manufacturers have run out of room for boosting CPU performance.
- Instead of driving clock speeds and straight-line instruction throughput higher, they turn to hyperthreading and multicore architectures.

The parallel programming model became necessary.

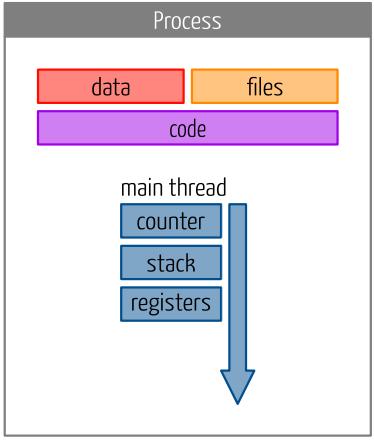
- The MPI standard was introduced by the MPI Forum in May 1994 and updated in June 1995.
- The OpenMP standard was introduced in 1997 (Fortran) and 1998 (C/C++).

Anatomy of an HPC cluster



- Multiple nodes
- Interconnected by a high-speed network
- The nodes consist of (a) processor(s) and local memory
- Communication is done via message passing

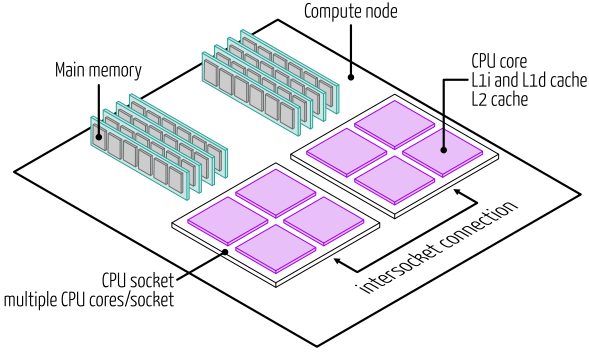
Process



- A process is an instance of an application
- A process is executed by at least one thread
- A process is a container describing the state of an application: code, memory mapping, shared libraries, ...

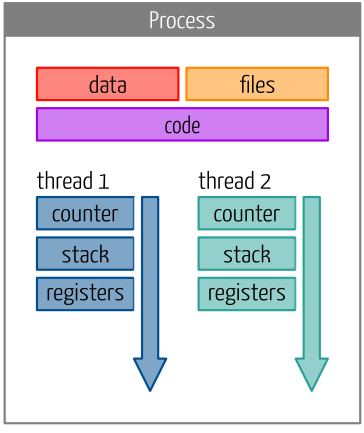
In scientific computing, the dominant paradigm for process parallelism is the single program multiple data model with MPI.

Anatomy of a Compute Node



- At least one multi-core CPU
- All CPUs can access a single memory address space
- Systems memory may be physically distributed, but logically shared
- Shared-memory programming model like OpenMP target a single compute node

Threads



- A thread is an independent stream of instructions that can be scheduled to run by the operating system.
- Multiple threads can exist within one process, and they share the memory
- A thread only the owns the bare essential resources to exist as an executable code: execution counter, stack pointer, registers and thread-specific data

In scientific computing the dominant paradigm for thread parallelism is OpenMP

What is OpenMP?

OpenMP is a shared-memory application programming interface which by adding directives to a sequential program describes how the work is shared among threads and order accesses to shared data.

OpenMP hides the low-level details and allows the programmer to describe the parallel code with high-level constructs.

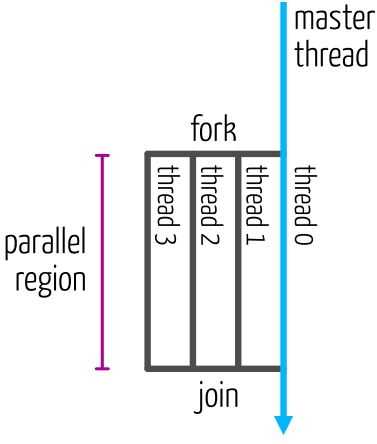
Why use threads?

The operating system does not need to create a new memory map for a new thread. It increases efficiency on multiprocessor systems.

Shared memory makes it trivial to share data among threads (with potential drawbacks though).

Fork-Join

OpenMP use the fork-join model



- The master thread continues after the fork operation
- The children threads begin operation separate from the master thread
- Parallel execution begins
- Children join after they finish
- The master thread waits until all the children join
- Join ends parallel execution. Sequential execution of the master thread continues

Fork-Join

In practice, threads are not created or destroyed for every parallel region.

OpenMP implementations use a thread pool to avoid the cost of thread creation and destruction at each fork and join.

After the join, the children thread go idle.

OpenMP is using directives

Directives are programming language constructs that specifies how a compiler should process its input

An OpenMP program is the combination of

- a base language (C, C++ or Fortran)
- annotations with OpenMP directives

Anatomy of an OpenMP directive

OpenMP directive in C/C++

```
#pragma omp construct [clauses]
```

OpenMP directive in Fortran

```
!$omp construct [clauses]
```

Anatomy of an OpenMP directive

OpenMP directive in C/C++


```
#pragma omp construct [clauses]
```

OpenMP directive in Fortran

```
!$omp construct [clauses]
```

Anatomy of an OpenMP directive

OpenMP directive in C/C++

```
#pragma omp construct [clauses]
```

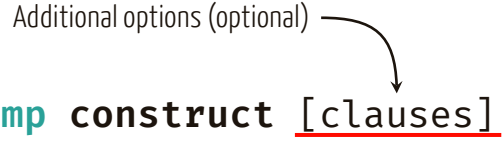

Give instruction on what to do

OpenMP directive in Fortran

```
!$omp construct [clauses]
```

Anatomy of an OpenMP directive

OpenMP directive in C/C++



OpenMP directive in Fortran

```
!$omp construct [clauses]
```

What the directives do

An OpenMP construct can specify

- the creation of a parallel region
- how to parallelize loops
- whether the variables in the parallel region are private or shared
- how/if the threads are synchronized
- how the work is divided between threads

The Advantages of Using directive

- Does not modify the serial implementation
- You can still compile and run the program as a serial code.
- Can be added incrementally allowing a gradual parallelization
- Easier to maintain

Hard work is hidden

Directives hide the actual parallelization work from the programmer

The compiler replaces the directives by the appropriate calls to the OpenMP runtime and library

Going Parallel

The Parallel Construct

Parallel construct in C/C++

Creates a parallel region by spawning a team of threads

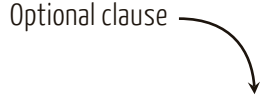

```
#pragma omp parallel [clauses]
  structured-block
```

Parallel construct in Fortran

```
!$omp parallel [clauses]
  structured-block
!$omp end parallel
```

The Parallel Construct

Parallel construct in C/C++




```
#pragma omp parallel [clauses]
  structured-block
```

Parallel construct in Fortran

```
!$omp parallel [clauses]
  structured-block
!$omp end parallel
```

The Parallel Construct

Parallel construct in C/C++

```
#pragma omp parallel [clauses]
  structured-block
```


Block of code

Parallel construct in Fortran

```
!$omp parallel [clauses]
  structured-block
!$omp end parallel
```

OpenMP Hello World

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

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

  #pragma omp parallel
  {
    printf("Hello, I'm thread %d of %d.\n",
           omp_get_thread_num(),
           omp_get_num_threads());
  }

  return 0;
}
```

```fortran
    program main
      use omp_lib

      !$omp parallel
        print 100, omp_get_thread_num(), &
&                  omp_get_num_threads()
100     format('Hello, I am thread ', i0, ' of ', i0)

      !$omp end parallel
    end program
```

- Include **`omp.h`** or use the **`omp_lib`** module to get access to the OpenMP runtime library
- Use the **`omp_get_thread_num`** to get the ID of the thread in the team and **`omp_get_num_threads`** functions to get the number of threads in the team

Compiling the OpenMP Hello World

To compile an OpenMP program, you need to pass a specific flag to the compiler

GCC:	gcc	-fopenmp
Clang:	clang	-fopenmp
Intel classic:	icc	-qopenmp
Intel DPC++:	icx	-fopenmp

This flag instructs the compiler to consider OpenMP directives

Compiling

For this course the GCC compiler is recommended. This compiler is made available once you have loaded the appropriate module:

```
module load releases/2020b GCC/10.2.0
```

These flags may be also be of interest:

`-march=native`	Generate instructions for the compiling machine
`-Wall -Wextra`	Enable most of the compiler warning
`-O3`	Enable most optimizations
`-Ofast`	Enable aggressive optimizations
`-fopt-info`	Provide an optimization report

Executing the OpenMP Hello World

The basic command to compile the OpenMP hello world is

```
 $ gcc -fopenmp -o example omp_helloworld.c
 $ OMP_NUM_THREADS=4 ./example
Hello, I'm thread 1 of 4.
Hello, I'm thread 2 of 4.
Hello, I'm thread 3 of 4.
Hello, I'm thread 0 of 4.
```

Notice that we use an environment variable in front of the command to launch our application

Executing the OpenMP Hello World

The `OMP_NUM_THREADS` environment variable allows you to specify the number of threads

```
export OMP_NUM_THREADS=4
./example
```

← 4 threads for the duration of the session

```
OMP_NUM_THREADS=4 ./example
```

← 4 threads for this execution of the program

```
OMP_NUM_THREADS=$SLURM_CPUS_PER_TASK ./example
```

← convenient way to determines the number of threads from a slurm script

Submitting an OpenMP Job

When submitting your OpenMP job to one of the CÉCI clusters set **`cpus-per-task`** to specify the number of threads.

```
#!/bin/bash
# Basic submission script for an openmp job
#SBATCH --time=01:00:00
#SBATCH --ntasks=1
#SBATCH --cpus-per-task=4
#SBATCH --mem-per-cpu=1024

export OMP_NUM_THREADS=$SLURM_CPUS_PER_TASK

module load releases/2020b
module load GCCcore/10.2.0

./your_omp_app
```

Making Things Go Parallel

Creating a parallel region does not mean that that the work will be shared among the threads. For example, if we consider this piece of code:

```c
int max_threads = omp_get_max_threads();
int* iterations = malloc(sizeof(int)*max_threads);

for(int i = 0; i < max_threads; ++i)
  iterations[i] = 0;

#pragma omp parallel
{
  int tid = omp_get_thread_num();

  for(int i = 0; i < 1000; ++i)
    iterations[tid]++;
}

for(int i = 0; i < max_threads; ++i)
  printf("Number of iteration for thread %d: %d\n",
         i, iterations[i]);
```

```fortran
      max_threads = omp_get_max_threads()
      allocate(iterations(0:max_threads-1))

      iterations = 0
      !$omp parallel private(tid)
        tid = omp_get_thread_num()

        do i = 1,1000
          iterations(tid) = iterations(tid) + 1
        end do
      !$omp end parallel

      do i = 0, max_threads-1
        print 100, i, iterations(i)
100     format('Number of iteration for thread ', i0, &
&             ': ', i0)
      end do
```

Making Things Go Parallel

```
 $ gcc -fopenmp -o example omp_iterations.c
 $ OMP_NUM_THREADS=4 ./example
Number of iteration for thread 0: 1000
Number of iteration for thread 1: 1000
Number of iteration for thread 2: 1000
Number of iteration for thread 3: 1000
```

There is no worksharing: all the threads execute all the iterations of the loop

Parallel $\neq$ Worksharing

The parallel construct means that

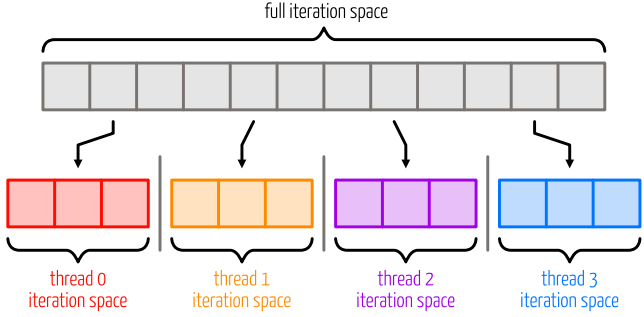
- a team of threads is created, i.e. there is a fork
- the code is executed redundantly by each thread
- the threads in the team join at the end of the region

but

- most scientific workloads can be parallelized by distributing the iterations of a loop among threads
- therefore the parallel construct is not sufficient we need a way to distribute the iterations

Worksharing

Worksharing a loop is dividing the iteration space into chunks and distribute these chunks to the threads



As the threads run in parallel, we can expect a `nthreads` speedup as each thread works on `niters/nthreads` iterations of the loop

Distributing iterations

One of the options for sharing the work between the threads is to define lower and higher bounds of the loop depending on the thread ID.

```c
int max_threads = omp_get_max_threads();
int* iterations = malloc(sizeof(int)*max_threads);

for(int i = 0; i < max_threads; ++i)
  iterations[i] = 0;

#pragma omp parallel
{
  int      tid = omp_get_thread_num();
  int nthreads = omp_get_num_threads();

  int  low = n * tid / nthreads;
  int high = n * (tid + 1) / nthreads;

  for(int i = low; i < high; ++i)
    iterations[tid]++;
}

for(int i = 0; i < max_threads; ++i)
  printf("Number of iteration for thread %d: %d\n",
         i, iterations[i]);
```

```fortran
      max_threads = omp_get_max_threads()
      allocate(iterations(0:max_threads-1))

      iterations = 0

      !$omp parallel private(tid)
        tid = omp_get_thread_num()
        nthreads = omp_get_num_threads()

         low = n * tid / nthreads + 1
        high = n * (tid + 1) / nthreads

        do i = low, high
          iterations(tid) = iterations(tid) + 1
        end do
      !$omp end parallel

      do i = 0, max_threads-1
        print 100, i, iterations(i)
100     format('Number of iteration for thread ', i0, &
&              ': ', i0)
      end do
```

Distributing iterations

```
 $ gcc -fopenmp -o example omp_iterations.c
 $ OMP_NUM_THREADS=4 ./example
Number of iteration for thread 0: 250
Number of iteration for thread 1: 250
Number of iteration for thread 2: 250
Number of iteration for thread 3: 250
```

Distributing iterations with a directive

Instead of computing the bounds, we can use the **`for`** (or **`do`**) construct.

```c
int max_threads = omp_get_max_threads();
int* iterations = malloc(sizeof(int)*max_threads);

for(int i = 0; i < max_threads; ++i)
  iterations[i] = 0;

#pragma omp parallel
{
  #pragma omp for
  for(int i = 0; i < n; ++i)
    iterations[tid]++;
}

for(int i = 0; i < max_threads; ++i)
  printf("Number of iteration for thread %d: %d\n",
         i, iterations[i]);
```

```fortran
      max_threads = omp_get_max_threads()
      allocate(iterations(0:max_threads-1))

      iterations = 0

      !$omp parallel private(tid)
        !$omp do
          do i = 1, n
            iterations(tid) = iterations(tid) + 1
          end do
        !$omp end do
      !$omp end parallel

      do i = 0, max_threads-1
        print 100, i, iterations(i)
100     format('Number of iteration for thread ', i0, &
&             ': ', i0)
      end do
```

Distributing iterations with a directive

```
 $ gcc -fopenmp -o example omp_for_iters.c
 $ OMP_NUM_THREADS=4 ./example
Number of iteration for thread 0: 250
Number of iteration for thread 1: 250
Number of iteration for thread 2: 250
Number of iteration for thread 3: 250
```

The Canonical for-loop

The for-loop needs to be in canonical form to be used with the **`for`** directive

```
#pragma omp for
for ([inttype] var = start; var <  end; ++var
                           <=       var++
                           >        var += incr
                           >=       var = var + incr
                                    var--, ...)
```

- **`var`** , cannot be modified in the loop body. It must be an integer (signed or unsigned), a pointer or random access iterator type
- **`start`** , **`end`** and **`incr`** must be loop invariant expressions, the number of iterations must be computable when the loop begins

Parallel Region Binding

In order for the iterations of a loop to be shared among the threads by a **`for`** /**`do`** , the construct needs a parallel region to bind to. If we take the previous example and remove the parallel region:

```c
int max_threads = omp_get_max_threads();
int* iterations = malloc(sizeof(int)*max_threads);

for(int i = 0; i < max_threads; ++i)
  iterations[i] = 0;

#pragma omp for
for(int i = 0; i < n; ++i)
  iterations[tid]++;

for(int i = 0; i < max_threads; ++i)
  printf("Number of iteration for thread %d: %d\n",
         i, iterations[i]);
```

```fortran
      max_threads = omp_get_max_threads()
      allocate(iterations(0:max_threads-1))

      iterations = 0

      !$omp do
        do i = 1, n
          iterations(tid) = iterations(tid) + 1
        end do
      !$omp end do

      do i = 0, max_threads-1
        print 100, i, iterations(i)
100     format('Number of iteration for thread ', i0, &
&             ': ', i0)
      end do
```

Parallel Region Binding

```
 $ OMP_NUM_THREADS=4 ./example
Number of iteration for thread 0: 1000
Number of iteration for thread 1: 0
Number of iteration for thread 2: 0
Number of iteration for thread 3: 0
```

As there was no parallel region to bind to, the **`for`** /**`do`** construct binds to the master thread.

Combined Directive

The following code snippet,

```
#pragma omp parallel
{
  #pragma omp for
  for(int i = 0; i < n; ++i)
    do_something()
}
```

```
!$omp parallel
  !$omp do
    do i = 1,n
      call do_something()
    end do
  !$omp end do
!$omp end parallel
```

may also be written as combined **`parallel`** and **`for`** directives

```
#pragma omp parallel for
for(int i = 0; i < n; ++i)
  do_something();
```

```
!$omp parallel do
  do i = 1,n
    call do_something()
  end do
!$omp end parallel do
```

Orphaning

- Directives are active in the dynamic scope of a parallel region, not just its lexical scope. This allows for orphaned directives.
- Orphaning is a situation when directives related to a parallel region are outside the lexical extent of the parallel region.
- Typical situation is calling a function containing a worksharing directive from a parallel region.

Orphaning Example

```c
// [...]

void ax(int n, double alpha, double* x) {
  int nthreads = omp_get_num_threads();
  int tid = omp_get_thread_num();

  printf("Executing ax by thread %d of %d threads.\n", tid,
         nthreads);

  int niters = 0;

  #pragma omp for
  for (int i = 0; i < n; ++i) {
    x[i] = alpha * x[i];
    niters++;
  }

  printf("Thread with id %d did %d iterations.\n", tid, niters);
}

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

  #pragma omp parallel
  {
    ax(n, 3.0, x);
  }

  ax(n, 5.0, y);

  // [...]
```

```fortran
      ! [...]

      !$omp parallel
        call ax(n, 3.0d0, x)
      !$omp end parallel

      call ax(n, 5.0d0, y)

      ! [...]

      contains
        subroutine ax(n, alpha, x)
          ! [...]

          print 100, tid, nthreads
100       format('Executing ax by thread ', i0,
&                ' of ', i0, ' threads.')

          !$omp do
            do i = 1,n
              x(i) = alpha * x(i)
              niters = niters + 1
            end do
          !$omp end do

          print 200, tid, niters
200       format('Thread with id ', i0, &
&                ' did ', i0, ' iterations.')

          ! [...]
```

Orphaning Example

```
 $ gcc -fopenmp -o example omp_orphaned.c
 $ OMP_NUM_THREADS=4 ./example
Executing ax by thread 0 of 4 threads.
Executing ax by thread 2 of 4 threads.
Executing ax by thread 1 of 4 threads.
Executing ax by thread 3 of 4 threads.
Thread with id 0 did 250 iterations.
Thread with id 1 did 250 iterations.
Thread with id 2 did 250 iterations.
Thread with id 3 did 250 iterations.
Executing ax by thread 0 of 1 threads.
Thread with id 0 did 1000 iterations.
```

Loop collapsing

In some cases, you can collapse the loops into one in order to increase the run trip of the loop.

```
#pragma omp parallel for collapse(2)
for (int i = 0; i < 3; ++i) {
  for (int j = 0; j < n; ++j) {
    a[i][j] = do_something();
  }
}
```

```
!$omp parallel do collapse(2)
  do j = 1,3
    do i = 1,n
      a(i, j) = do_something()
    end do
  end do
!$omp end parallel do
```

This is particularly useful when one of the loops is not of sufficient length to have efficient parallelization.

Loop collapsing

The `collapse` clause, collapse the iterations of the n-associated loops to which the clause applies into one larger iteration space. This clause can only apply on tightly nested loops, meaning that there is no code between the loops.

```
#pragma omp for collapse(n)
  nested-for-loops
```

```
!$omp do collapse(n)
  nested-do-loops
```

Data Sharing in a Parallel World

Hello Again

Let's go back to the hello world code:

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

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

  #pragma omp parallel
  {
    tid = omp_get_thread_num();
    nthreads = omp_get_num_threads();

    printf("Hello, I'm thread %d of %d.\n", tid, nthreads);
  }

  return 0;
}
```

```fortran
program main
  use omp_lib

  implicit none

  integer :: nthreads, tid

  !$omp parallel
    tid = omp_get_thread_num()
    nthreads = omp_get_num_threads()

    print 100, tid, nthreads
100 format('Hello, I am thread ', i0,' of ', i0, '.')
  !$omp end parallel
end program
```

Hello Again

Most of the time, the program output is what is expected but, ...

```
 $ OMP_NUM_THREADS=4 ./example
Hello, I'm thread 2 of 4.
Hello, I'm thread 2 of 4.
Hello, I'm thread 2 of 4.
Hello, I'm thread 3 of 4.
```

... occasionally, we have imposters pretending to be thread 2.

What's wrong?

All variables declared outside of the scope of an OpenMP `parallel` construct is shared by all threads by default.

```
int nthreads, tid;
#pragma omp parallel
{
  tid = omp_get_thread_num();
  nthreads = omp_get_num_threads();

  printf("Hello, I'm thread %d of %d.\n",
         tid, nthreads);
}
```

declaration outside of the OpenMP construct, theses variables are shared by all threads

What's wrong?

All variables declared outside of the scope of an OpenMP **`parallel`** construct is shared by all threads by default.

```
int nthreads, tid;
#pragma omp parallel
{
  tid = omp_get_thread_num();
  nthreads = omp_get_num_threads();

  printf("Hello, I'm thread %d of %d.\n",
         tid, nthreads);
}
```

all threads write to the same location

What's wrong?

All variables declared outside of the scope of an OpenMP `parallel` construct is shared by all threads by default.

```
int nthreads, tid;
#pragma omp parallel
{
  tid = omp_get_thread_num();
  nthreads = omp_get_num_threads();

  printf("Hello, I'm thread %d of %d.\n",
         tid, nthreads);
}
```

the same here, but, as the value is the same for all threads, it's less likely to go wrong

What's wrong?

All variables declared outside of the scope of an OpenMP `parallel` construct is shared by all threads by default.

```
int nthreads, tid;
#pragma omp parallel
{
  tid = omp_get_thread_num();
  nthreads = omp_get_num_threads();

  printf("Hello, I'm thread %d of %d.\n",
         tid, nthreads);
}
```

when the values are used here, another thread may have modified them

What's wrong?

All variables declared outside of the scope of an OpenMP `parallel` construct is shared by all threads by default.

```
int nthreads, tid;
#pragma omp parallel
{
  tid = omp_get_thread_num();
  nthreads = omp_get_num_threads();

  printf("Hello, I'm thread %d of %d.\n",
         tid, nthreads);
}
```

We created a data race

Data Race

A data race is when one or more threads concurrently access a location in memory or a variable, at least one of which is a write.

```
int x = 0;
#pragma omp parallel
{
  x = x + 1;
}
```

Thread 1	Thread 2		x (in memory)
			0
load x		$\leftarrow$	0
$x + 1$	load x	$\leftarrow$	0
store x	$x + 1$	$\rightarrow$	1
	store x	$\rightarrow$	1

Data Race

Because of the potential data races in shared-memory parallel programs, extra care is needed as this is not always easy to spot

- with floating-point data, it may be difficult to distinguish from a numerical side effect
- changing the number of threads can cause the problem to seemingly (dis)appear
- may depend on the load on the system
- may only show up using many threads

Data Race

In the previous example, we executed `x+1` twice and get `1` as a result (while `2` was expected)

We need a way to prevent data race from happening: only share data that are not modified by other threads.

Hello Again (Data Race Free)

The solution to avoid a data race is to declare the **`nthreads`** and **`tid`** variables as private to the threads.

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

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

  #pragma omp parallel private(nthreads, tid)
  {
    tid = omp_get_thread_num();
    nthreads = omp_get_num_threads();

    printf("Hello, I'm thread %d of %d.\n", tid, nthreads);
  }

  return 0;
}
```

```fortran
program main
  use omp_lib

  implicit none

  integer :: nthreads, tid

  !$omp parallel private(nthreads, tid)
    tid = omp_get_thread_num()
    nthreads = omp_get_num_threads()

    print 100, tid, nthreads
100 format('Hello, I am thread ', i0,' of ', i0, '.')
  !$omp end parallel
end program
```

Data-Sharing Attributes

```
private( list )
```

The parallel construct can take one or more data-sharing clause. The first one is **`private`**, which instruct that each thread should have its own instance of the listed variables. The initial value when we enter the parallel region is undefined.

Data-Sharing Attributes

```
firstprivate( list )
```

If the value of the variable before entering the parallel region matters, we can use **`firstprivate`** which is the same as **`private`** but, the variable should be initialized with its value before the **`parallel`** construct.

Data-Sharing Attributes

```
shared( list )
```

The third option is to declare a variable as **`shared`** which indicates that the variables listed should be shared among all threads. This is the default.

Data-Sharing Attributes

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

You can change the default data-sharing attribute with the **`default`** clause. Setting the value to **`none`** will force you to specify the data-sharing attribute for all your .

Data-Sharing Attributes Example

```c
int x = 1, y = 2;
int z = 3, a = 4;
#pragma omp parallel private(x) firstprivate(y) shared(z)
{
  x = x + z;
  y = y + z;
  a = a + 1;

  printf("Thread %d: x = %d, y = %d, z = %d\n",
         tid, x, y, z);
}

printf("Final: x = %d, y = %d, z = %d, a = %d\n",
       x, y, z, a);
```

```fortran
    integer :: x = 1, y = 2
    integer :: z = 3, a = 4
    !$omp parallel private(x) firstprivate(y) shared(z)
      x = x + z
      y = y + z
      a = a + 1

      print 100, tid, x, y, z
100   format('Thread ', i0, ': x = ', i0, &
&            ', y = ', i0, ', z = ', i0)
    !$omp end parallel

    print 200, x, y, z, a
200 format('Final: x = ', i0, ', y = ', i0, &
&          ', z = ', i0, ', a = ', i0)
```

Data-Sharing Attributes Example

```
 $ OMP_NUM_THREADS=4 ./example
Thread 0: x = 3, y = 5, z = 3
Thread 1: x = 32674, y = 5, z = 3
Thread 3: x = 32674, y = 5, z = 3
Thread 2: x = 32674, y = 5, z = 3
Final: x = 1, y = 2, z = 3, a = 7
```

Data-Sharing Attributes Example

```
 $ OMP_NUM_THREADS=4 ./example
Thread 0: x = 4, y = 5, z = 3
Thread 1: x = 32674, y = 5, z = 3
Thread 3: x = 32674, y = 5, z = 3
Thread 2: x = 32674, y = 5, z = 3
Final: x = 1, y = 2, z = 3, a = 7
```

The value of `x` is wrong because using the `private` clause the value of the variable is undefined when entering the `parallel` construct.

Data-Sharing Attributes Example

```
 $ OMP_NUM_THREADS=4 ./example
Thread 0: x = 4, y = 5, z = 3
Thread 1: x = 32674, y = 5, z = 3
Thread 3: x = 32674, y = 5, z = 3
Thread 2: x = 32674, y = 5, z = 3
Final: x = 1, y = 2, z = 3, a = 7
```

The value of **`y`** , on the other hand, is correct as the **`firstprivate`** clause sets the initial value in the **`parallel`** construct to be the value before entering the construct.

Data-Sharing Attributes Example

```
 $ OMP_NUM_THREADS=4 ./example
Thread 0: x = 4, y = 5, z = 3
Thread 1: x = 32674, y = 5, z = 3
Thread 3: x = 32674, y = 5, z = 3
Thread 2: x = 32674, y = 5, z = 3
Final: x = 1, y = 2, z = 3, a = 7
```

After the **`parallel`** region, the values of the private variables are the same as before the region.

Data-Sharing Attributes Example

```
 $ OMP_NUM_THREADS=4 ./example
Thread 0: x = 4, y = 5, z = 3
Thread 1: x = 32674, y = 5, z = 3
Thread 3: x = 32674, y = 5, z = 3
Thread 2: x = 32674, y = 5, z = 3
Final: x = 1, y = 2, z = 3, a = 7
```

The value of `z` never changes. This variable is shared but never modified.

Data-Sharing Attributes Example

```
 $ OMP_NUM_THREADS=4 ./example
Thread 0: x = 4, y = 5, z = 3
Thread 1: x = 32674, y = 5, z = 3
Thread 3: x = 32674, y = 5, z = 3
Thread 2: x = 32674, y = 5, z = 3
Final: x = 1, y = 2, z = 3, a = 7
```

We did not specify any data-sharing attribute for `a` . Thus, this variable has the default attribute and is shared. We see that there is a data race problem as we expected the final value to be 8 with 4 threads.

Data-Sharing Attribute Rules

Variables with automatic storage duration that are declared in a scope inside the construct are private.

```
#pragma omp parallel
{
  int a = 3; // private
}
```

Data-Sharing Attribute Rules

Variables with static storage duration that are declared in a scope inside the construct are shared.

```
#pragma omp parallel
{
  static int a; // shared
}
```

Data-Sharing Attribute Rules

The loop iteration variable(s) in the associated for-loop(s) of a **`for`** construct is (are) private.

```
int i;
#pragma omp parallel
{
  #pragma omp for
  for(i = 0; i < n; ++i) // i is private
  {
    // ...
  }
}
```

Data-Sharing Attribute Rules

Objects with dynamic storage duration are shared (allocated by malloc).

```
int* a = (int*)malloc(n * sizeof(int));

#pragma omp parallel
{
  // the array a can not be privatized
  // all threads can read and write the
  // whole array
  a[0] = 3;
}
```

Good Practices

Set the default data attribute to `none` with `default(none)`.

- You will get a compiler error if you do not explicitly specify the data attribute of your variables
- It forces you to think about the data attribute of your variables

Loop Carried Data Dependency

The fact that dynamically allocated objects cannot be private implies that particular care must be taken when handling arrays.

```
#pragma omp parallel
{
  #pragma omp for
  for(int i = 0; i < (n-1); ++i)
    a[i] = a[i+1]+ b[i];
}
```

```
!$omp parallel
  !$omp do
    do i = 1,n-1
      a(i) = a(i+1) + b(i)
    end do
  !$omp end do
!$omp end parallel
```

Loop Carried Data Dependency

A **loop carried data dependency** occurs when a value written in one loop iteration is read or written by another iteration.

Thread 1	Thread 2
`a[0] = a[1] + b[0]`	`a[4] = a[5] + b[4]`
`a[1] = a[2] + b[1]`	`a[5] = a[2] + b[5]`
`a[2] = a[3] + b[2]`	`a[6] = a[3] + b[6]`
`a[3] = a[4] + b[3]`	`a[7] = a[4] + b[7]`

Synchronization

Synchronization

Synchronization ensures that two or more threads do not simultaneously execute some part of the program.

Synchronization may be needed for various reasons:

- makes sure that a particular operation is only executed once
- to avoid conflicts when accessing shared data
- ensure the order in which tasks are executed

Barrier

A `barrier` directive is a synchronization point at which the threads in a parallel region will wait until all other threads in that section reach the same point.

- When a first thread reaches the barrier, it waits
- When a second thread reaches the barrier, it does the same thing and so on
- When the last thread reaches the barrier, all the threads resume execution

Barrier

Most common usage of a barrier is to make sure that the value set by a thread is correctly defined before reading it from another thread.

```c
#pragma omp parallel private(tid, neighb)
{
  tid = omp_get_thread_num();
  neighb = tid - 1;

  if (tid == 0)
    neighb = omp_get_num_threads() - 1;

  a[tid] = a[tid] * 3.5;

  #pragma omp barrier

  b[tid] = a[neighb] + c;
}
```

```fortran
!$omp parallel private(tid, neighb, nthreads)
       tid = omp_get_thread_num()
  nthreads = omp_get_num_threads()
    neighb = tid - 1

  if (tid .eq. 0) neighb = nthreads - 1

  a(tid) = a(tid) * 3.5

  !$omp barrier

  b(tid) = a(neighb) + c
!$omp end parallel
```

Implicit Barrier

Some constructs in OpenMP have an implicit barrier. This is the case for the `parallel` and `for`/`do` constructs.

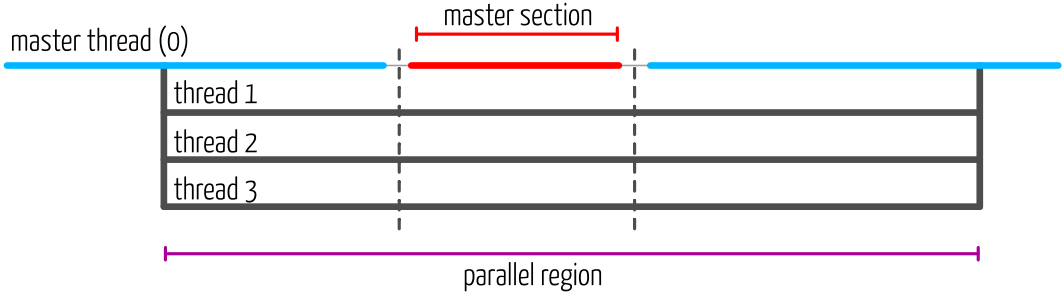
```
#pragma omp parallel
{
  #pragma omp for
  for (int i = 0; i < n; ++i) {

    // ...

  } <-- Implicit barrier, wait for all the threads to finish their iterations

  // ...

} <-- Implicit barrier, wait for all the threads to join
```

Master Directive

A `master` construct specifies a block of code that should be executed only by the master thread of the team.

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

```
!$omp master
  structured-block
!$omp end master
```



Hello World, Master Edition

Let's revisit the hello world program but, this time, only the master thread print the number of threads in the team.

```c
#pragma omp parallel
{
  printf("Hello, I'm thread %d\n",
         omp_get_thread_num());

  #pragma omp master
  {
    printf("There is %d threads in the team\n",
           omp_get_num_threads());
  }
}
```

```fortran
      !$omp parallel
        print 100, omp_get_thread_num()
100     format('Hello, I am thread ', i0)

        !$omp master
          print 200, omp_get_num_threads()
200       format('There is ', i0, &
&                ' threads in the team')
        !$omp end master
      !$omp end parallel
```

Hello World, Master Edition

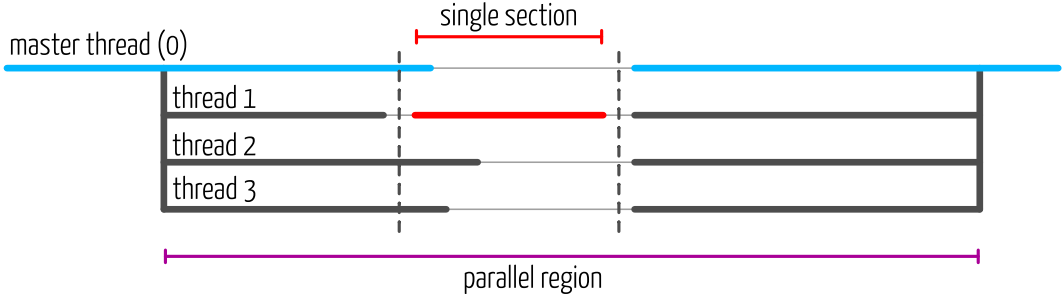
```
 $ gcc -fopenmp -o example omp_helloworld_master.c
 $ OMP_NUM_THREADS=4 ./example
Hello, I'm thread 3
Hello, I'm thread 0
There is 4 threads in the team
Hello, I'm thread 2
Hello, I'm thread 1
```

Single Directive

A `single` directive is executed by only one of the threads in the team (not necessarily the master thread). There is an implicit barrier at the end.

```
#pragma omp single
  structured-block
```

```
!$omp single
  structured-block
!$omp end single
```



Hello World, Single Edition

Let's revisit the hello world program using the single construct. This time we illustrate the most common usage of the single construct, that is, assign a value to a shared variable.

```c
#pragma omp parallel private(tid)
{
  tid = omp_get_thread_num();

  #pragma omp single
  {
    nthreads = omp_get_num_threads();

    printf("Hello, I'm thread %d of %d"
           " in the single construct.\n",
           tid, nthreads);
  }

  printf("Hello, I'm thread %d of %d.\n",
         tid, nthreads);
}
```

```fortran
      !$omp parallel private(tid)
        !$omp single
          nthreads = omp_get_num_threads()

          print 100, tid, nthreads
100       format('Hello, I am thread ', i0, &
&                ' of ', i0, &
&                ' in the single construct.')
        !$omp end single

        tid = omp_get_thread_num()

        print 200, tid, nthreads
200     format('Hello, I am thread ', i0, &
&              ' of ', i0, '.')
      !$omp end parallel
```

Hello World, Single Edition

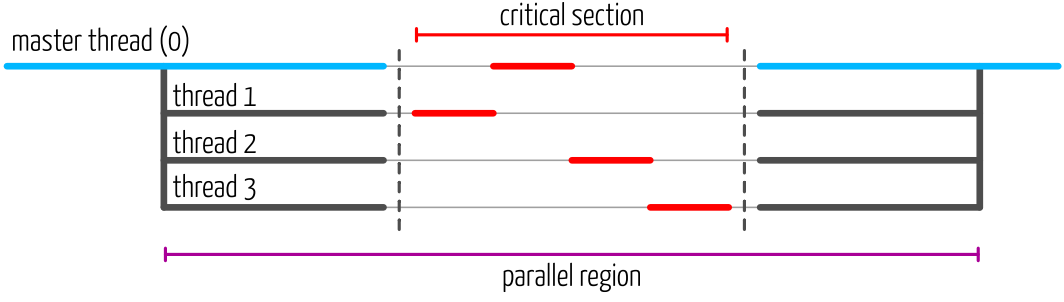
```
 $ gcc -fopenmp -o example omp_helloworld_single.c
 $ OMP_NUM_THREADS=4 ./example
Hello, I'm thread 3 of 4 in the single construct.
Hello, I'm thread 3 of 4.
Hello, I'm thread 2 of 4.
Hello, I'm thread 0 of 4.
Hello, I'm thread 1 of 4.
```

Critical Section

A `critical` section restricts execution of the associated structured block to one thread at a time.

```
#pragma omp critical
  structured-block
```

```
!$omp critical
  structured-block
!$omp end critical
```



Critical Section

Critical section is mostly used to update shared variables avoiding a data race.

```c
#pragma omp parallel private(tid, local_sum)
{
  tid = omp_get_thread_num();
  local_sum = 0;

  #pragma omp for
  for (int i = 0; i < n; ++i)
      local_sum += a[i];

  #pragma omp critical
  {
    sum += local_sum;
    printf("Thread %d: local sum = %d, sum = %d.\n",
           tid, local_sum, sum);
  }
}

printf("Sum after parallel region: %d.\n", sum);
```

```fortran
    !$omp parallel private(tid, local_sum)
      tid = omp_get_thread_num()
      local_sum = 0

      !$omp do
        do i = 1,n
          local_sum = local_sum + a(i)
        end do
      !$omp end do

      !$omp critical
        global_sum = global_sum + local_sum

        print 100, tid, local_sum, global_sum
100     format('Thread ', i0, ': local sum = ', i0, &
&              ', sum = ', i0, '.')
      !$omp end critical
    !$omp end parallel

    print*, 'Sum after parallel region:', global_sum
```

Critical Section

Critical section is mostly used to update shared variables avoiding a data race.

```
#pragma omp parallel shared(sum) private(tid, local_sum)
{
  tid = omp_get_thread_num();
  local_sum = 0;

  #pragma omp for
  for (int i = 0; i < n; ++i)
      local_sum += a[i];

  #pragma omp critical
  {
    sum += local_sum;
    printf("Thread %d: local sum = %d, sum = %d.\n",
            tid, local_sum, sum);
  }
}

printf("Sum after parallel region: %d.\n", sum);
```

Critical section to update the global sum. Without the critical section, there is a potential data race here

Critical Section

```
 $ gcc -fopenmp -o example omp_critical.c
 $ OMP_NUM_THREADS=4 ./example
Thread 0: local sum = 300, sum = 300.
Thread 3: local sum = 2175, sum = 2475.
Thread 1: local sum = 925, sum = 3400.
Thread 2: local sum = 1550, sum = 4950.
Sum after parallel region: 4950.
```

Named Critical Section

- A thread waits at the beginning of a critical section until no other thread is executing a critical section with the same name
- All unnamed critical directives map to the same name
- Critical section names are global to the program

Named Critical Section

```c
#pragma omp critical (sum)
{
  sum += local_sum;
  printf("Thread %d: local sum = %d,"
         " sum = %d.\n",
         tid, local_sum, sum);
}

#pragma omp critical (max)
{
  max = MAX(max, local_max);
  printf("Thread %d: local max = %d,"
        " max = %d.\n",
         tid, local_max, max);
}
```

```fortran
!$omp critical (sum)
  global_sum = global_sum + local_sum;
  print 100, tid, 'sum', local_sum, &
&                 'sum', global_sum
!$omp end critical (sum)

!$omp critical (max)
  global_max = max(global_max, local_max)
  print 100, tid, 'max', local_max, &
&                 'max', global_max
!$omp end critical (max)
```

Named Critical Section

```
#pragma omp critical (sum)
{
  sum += local_sum;
  printf("Thread %d: local sum = %d, sum = %d.\n",
          tid, local_sum, sum);
}

#pragma omp critical (max)
{
  max = MAX(max, local_max);
  printf("Thread %d: local max = %d, max = %d.\n",
          tid, local_max, max);
}
```

First critical section for the global sum

Named Critical Section

```
#pragma omp critical (sum)
{
  sum += local_sum;
  printf("Thread %d: local sum = %d, sum = %d.\n",
          tid, local_sum, sum);
}

#pragma omp critical (max)
{
  max = MAX(max, local_max);
  printf("Thread %d: local max = %d, max = %d.\n",
          tid, local_max, max);
}
```

First critical section for the global sum

Second critical section for the global maximum. A thread can be in the first section while an other is in the second one

Named Critical Section

```
 $ gcc -fopenmp -o example omp_critical_named.c
 $ OMP_NUM_THREADS=4 ./example
Thread 3: local sum = 2175, sum = 2175.
Thread 3: local max = 99, max = 99.
Thread 1: local sum = 925, sum = 3100.
Thread 1: local max = 49, max = 99.
Thread 2: local sum = 1550, sum = 4650.
Thread 0: local sum = 300, sum = 4950.
Thread 2: local max = 74, max = 99.
Thread 0: local max = 24, max = 99.
Sum after parallel region: 4950.
Max after parallel region: 99.
```

The `nowait` Clause

```
//...

  #pragma omp for
  for (int i = 0; i < n; ++i) {
      local_sum += a[i];
  } <-------------------- There is an implicit barrier here

  #pragma omp critical
  {
    sum += local_sum;
    printf("Thread %d: local sum = %d, sum = %d.\n",
            tid, local_sum, sum);
  }
}

// ...
```

The `nowait` Clause

```
//...

  #pragma omp for
  for (int i = 0; i < n; ++i) {
      local_sum += a[i];
  }

  #pragma omp critical
  {
    sum += local_sum;
    printf("Thread %d: local sum = %d, sum = %d.\n",
            tid, local_sum, sum);
  }
}

// ...
```

There is no need to wait for the other threads to finish the iterations to execute the critical section

The `nowait` Clause

```
//...

  #pragma omp for nowait
  for (int i = 0; i < n; ++i) {
      local_sum += a[i];
  }

  #pragma omp critical
  {
    sum += local_sum;
    printf("Thread %d: local sum = %d, sum = %d.\n",
            tid, local_sum, sum);
  }
}

// ...
```

We add a `nowait` clause to the directive

The implicit barrier at the end of the loop is lifted

The `nowait` Clause

The **`nowait`** clause applied to a **`for`** construct remove the implicit barrier at the end of the construct.

```
#pragma omp for nowait
  structured-block
```

```
!$omp do
  structured-block
!$omp end do nowait
```

The **`nowait`** clause can also be applied to a **`single`** directive.

```
#pragma omp single nowait
  structured-block
```

```
!$omp do
  structured-block
!$omp end single nowait
```

The `nowait` Clause

The **`nowait`** clause can also be convenient when the work in two different loops are independent from each other.

```
#pragma omp parallel
{
  #pragma omp for
  for (int i = 0; i < n; ++i) {
    d[i] = a[i] + b[i];
  }

  #pragma omp for nowait
  for (int i = 0; i < n; ++i) {
    e[i] = a[i] + c[i];
  }
}
```

```
!$omp parallel
{
  !$omp do
    do i = 1,n
      d(i) = a(i) + b(i)
    end do
  !$omp end do nowait

  !$omp do
    do i = 1,n
      e(i) = a(i) + c(i)
    end do
  !$omp end do nowait
!$omp end parallel
```

The `nowait` Clause

The **`nowait`** clause can also be convenient when the work in two different loops are independent from each other.

```
#pragma omp parallel
{
  #pragma omp for nowait
  for (int i = 0; i < n; ++i) {
      d[i] = a[i] + b[i];
  } <-------------------- No barrier at the end of the loop

  #pragma omp for nowait
  for (int i = 0; i < n; ++i) { <-- The threads start the iterations of this loop as soon as they finish their work in the first loop
      e[i] = a[i] + c[i];
  }
}
```

The `nowait` Clause

The **`nowait`** clause can also be convenient when the work in two different loops are independent from each other.

```
#pragma omp parallel
{
  #pragma omp for nowait
  for (int i = 0; i < n; ++i) {
      d[i] = a[i] + b[i];
  }

  #pragma omp for nowait
  for (int i = 0; i < n; ++i) {
      e[i] = a[i] + c[i];
  }
}
```

← Implicit barrier at the end of the **`parallel`** region

Reduction

The `reduction` clause avoid data races when summing or combining values. This clause can be applied to the `parallel` and `for` constructs

```
reduction(op:list)
```

`op` is an operator:

- Arithmetic reductions: `+ * - max min`
- Logical operator reductions: `& && | ||`

Reduction

The sum and maximum example using critical region can be rewritten with **`reduction`** clauses instead

```c
#pragma omp parallel for reduction(+:sum) \
                         reduction(max:max)
for (int i = 0; i < n; ++i) {
    sum += a[i];
    max = MAX(max, a[i]);
}

printf("Sum after parallel region: %d.\n", sum);
printf("Max after parallel region: %d.\n", max);
```

```fortran
!$omp  parallel for reduction(+:sum) &
!$omp&              reduction(max:imax)
  do i = 1,n
    sum += sum + a(i)
    imax = max(imax, a(i))
  end do
!$omp end parallel for

print*, 'Sum after parallel region: ', sum
print*, 'Max after parallel region: ', imax
```

Atomic operation

An atomic operation is an operation that will always be executed without any other thread being able to read or change state that is read or changed during the operation.

```
#pragma omp atomic [atomic-clause]
  expression-statement
```

Atomic operation

```
#pragma omp atomic atomic-clause
  expression-statement
```

The value of `atomic-clause` can be one of the following: `read`, `write`, `update` and `capture`. If no `atomic-clause` is specified, the default value is `update`.

Atomic operation: Read and Write

The `read` clause allows for the atomic read of `x`.

```
#pragma omp atomic read
v = x;
```

The `write` clause allows for the atomic write of `x`. Here, `expr` is an expression with scalar type, i.e. the result of the expression is a scalar.

```
#pragma omp atomic write
x = expr;
```

Atomic operation: Update

The `update` clause allows for the atomic update of `x` .

```
#pragma omp atomic update
  expression-statement
```

Expression statement

```
    x++;            x--;              ++x;        --x;

x op= expr;  x = x op expr;  x = expr op x;
```

Atomic operation: Capture

The `capture` clause allows for atomic update of the location designated by `x` while also capturing the original or final value of the location designated by `x`.

```
#pragma omp atomic update
  expression-statement
```

Expression statement

```
v = x++;  v = x--;  v = ++x;  v = --x;

 v = x op= expr;    v = x = x op expr;

          v = x = expr op x;
```

Atomic operation: Capture

The `capture` clause allows for atomic update of the location designated by `x` while also capturing the original or final value of the location designated by `x`.

```
#pragma omp atomic update
  structured-block
```

Structured block (part. 1)

`{ v = x; x op= expr; }`	`{ x op= expr; v = x; }`
`{ v = x; x = x op expr; }`	`{ v = x; x = expr op x; }`
`{ x = x op expr; v = x; }`	`{ x = expr op x; v = x; }`

Atomic operation: Capture

The `capture` clause allows for atomic update of the location designated by `x` while also capturing the original or final value of the location designated by `x`.

```
#pragma omp atomic update
  structured-block
```

Structured block (part. 2)

```
{ v = x; x++; }  { v = x; ++x; }  { ++x; v = x; }
{ x++; v = x; }  { v = x; x--; }  { v = x; --x; }
{ --x; v = x; }  { x--; v = x; }
```

Atomic example

The previous example of the summation of the elements of an array using a **critical** construct can be rewritten using an **atomic** update.

```
#pragma omp for
for (int i = 0; i < n; ++i) {
  local_sum += a[i];
}

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

```
!$omp do
do i = 1,n
  local_sum += local_sum + a(i)
end do
!$omp end do

!$omp atomic
  sum = sum + local_sum
!$omp end atomic
```

Atomic example

```
for (i = 0; i < 10000; ++i) {
  index[i] = i % 1000;
  y[i] = 0.0;
}

for (i = 0; i < 1000; ++i)
  x[i] = 0.0;

#pragma omp parallel for
for (i = 0; i < 10000; ++i) {
  #pragma omp atomic update
  x[index[i]] += 1.0 * i;

  y[i] += 2.0 * i;
}
```

```
do i = 1,10000
  inds(i) = mod(i, 1000)
  y(i) = 0.0
end do

do i = 1,1000
  x(i) = 0.0
end do

!$omp parallel do
  do i = 1,10000
    !$omp atomic update
    x(inds(i)) = x(inds(i)) + 1.0 * i

    y(i) = y(i) + 2.0 * i
  end do
!$omp end parallel do
```

Atomic example

```
for (i = 0; i < 10000; ++i) {
  index[i] = i % 1000;
  y[i] = 0.0;
}

for (i = 0; i < 1000; ++i)
  x[i] = 0.0;

#pragma omp parallel for
for (i = 0; i < 10000; ++i) {
  #pragma omp atomic update
  x[index[i]] += 1.0 * i;

  y[i] += 2.0 * i;
}
```

The advantage of using **atomic** in this example is that it allows updates of two different elements of **x** in parallel. If a **critical** construct were used, all updates to elements of **x** would be executed serially

Atomic vs. Critical

Safely increasing the value of `count` in parallel can be done either by using an `atomic` or a `critical` directive

```
#pragma omp atomic
  count++;
```

- An atomic operation has much lower overhead but the set of possible operations is restricted
- It can take advantage of hardware support for atomic operations

```
#pragma omp critical
  count++;
```

- A critical section can surround any arbitrary block of code
- There is a significant overhead when a thread enters and exits the critical section

Atomic vs. Reduction

Don't use **atomic** operation this way:

```
#pragma omp parallel for
for (int i = 0; i < n; ++i) {
  #pragma omp atomic
  sum += a[i];
}
```

```
!$omp parallel do
  do i = 1,n
    !$omp atomic
      sum = sum + a(i)
  end do
!$omp end parallel do
```

It is better to use a **reduction** clause:

```
#pragma omp parallel for reduction(+sum)
for (int i = 0; i < n; ++i) {
  sum += a[i];
}
```

```
!$omp parallel do reduction(+sum)
  do i = 1,n
    sum = sum + a(i)
  end do
!$omp end parallel do
```

Performance Considerations

- Avoid or minimize the use of `barrier` and `critical` sections.
- Use the `nowait` clause where possible to eliminate unnecessary barriers
- Favour the use of `master` instead of `single`

Loop Scheduling

Loop Scheduling

Loop scheduling, specify how iterations of a loop are divided into contiguous non-empty subsets (chunks), and how these chunks are distributed to the threads. Changing the loop scheduling is possible to use the **`schedule`** clause.

```
#pragma omp for schedule(kind, chunk)
  for-loop
```

```
!$omp do schedule(kind, chunk)
  do-loop
!$omp end do
```

Where the value of **`kind`** can be **`static`** , **`dynamic`** , **`guided`** or **`runtime`** . The default scheduling is **`static`** . The optional **`chunk`** may have different behaviour depending on the scheduling.

Static Loop Scheduling

With `static` loop scheduling, iterations are divided into chunks and the chunks are assigned to the threads. Each chunk contains the same number of iterations, except for the chunk that contains the last iteration, which may have fewer iterations.

```
#pragma omp for schedule(static)
  for-loop
```

```
!$omp do schedule(static)
  do-loop
!$omp end do
```

You can also provide a chunk size

```
#pragma omp for schedule(static, 100)
  for-loop
```

```
!$omp do schedule(static, 100)
  do-loop
!$omp end do
```

Dynamic Loop Scheduling

With `dynamic` loop scheduling, the iterations are distributed to threads in chunks. Each thread executes a chunk of iterations, then requests another chunk, until no chunks remain to be distributed.

```
#pragma omp for schedule(dynamic)
  for-loop
```

```
!$omp do schedule(dynamic)
  do-loop
!$omp end do
```

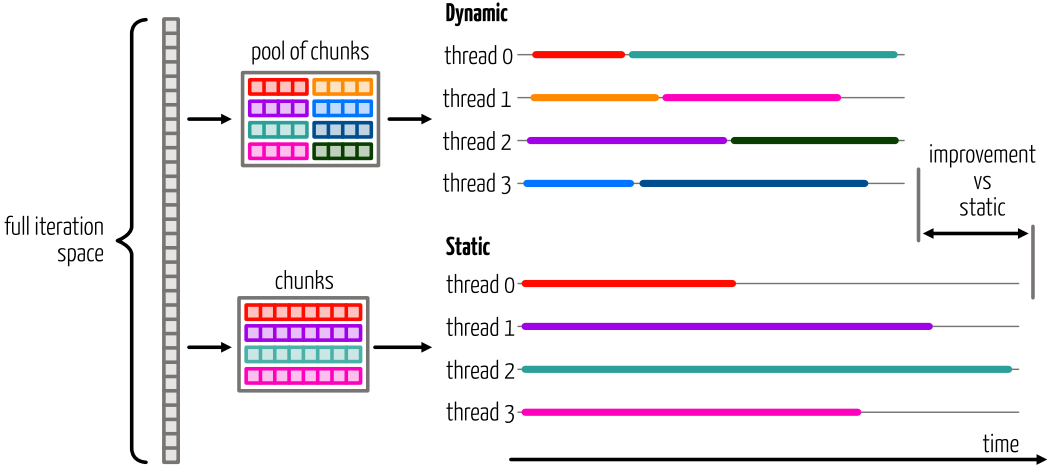
You can also provide a chunk size

```
#pragma omp for schedule(dynamic, 100)
  for-loop
```

```
!$omp do schedule(dynamic, 100)
  do-loop
!$omp end do
```

Dynamic Loop Scheduling

Dynamic scheduling particularly relevant when the amount of work of the loop iteration is not constant.

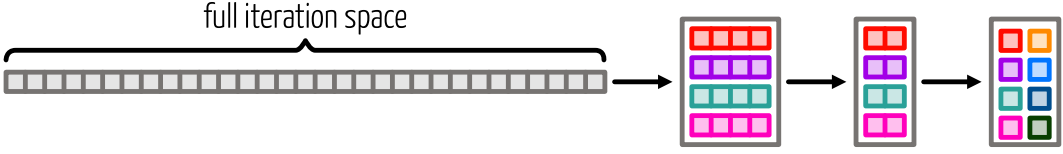


Guided Loop Scheduling

The **guided** loop scheduling is similar to the **dynamic** scheduling except that the size of each chunk is proportional to the number of unassigned iterations, decreasing to one.

```
#pragma omp for schedule(guided)
  for-loop
```

```
!$omp do schedule(guided)
  do-loop
!$omp end do
```



Why Using the Scheduling Clause?

- The default scheduling, `static` with a `chunk` size equals to `niter/nthreads` is not ideal for all workload.
- It may be the case that iterations of high index represent more work. In that case, some of the threads will finish early and have nothing to do. We have a load imbalance.
- Changing the scheduling may help balance the amount of work between the threads.

Example: Number of Prime Numbers

```
int prime, sum = 0;
#pragma omp parallel shared(n) private(prime)
{
  #pragma omp for reduction(+:sum)
  for (int i = 2; i <= n; i++) {
    prime = 1;

    for (int j = 2; j < i; j++) {
      if ( i % j == 0 ) {
        prime = 0;
        break;
      }
    }

    sum += prime;
  }
}
```

Trip count of this loop may be very low or very high depending if the number is prime or not

Example: Number of Prime Numbers

```
int prime, sum = 0;
#pragma omp parallel shared(n) private(prime)
{
  #pragma omp for reduction(+:sum)
  for (int i = 2; i <= n; i++) {
    prime = 1;

    for (int j = 2; j < i; j++) {
      if ( i % j == 0 ) {
        prime = 0;
        break; <-- If the number is not a prime number, we have an early exit
      }
    }

    sum += prime;
  }
}
```

Example: Number of Prime Numbers

```
$ gcc -fopenmp -o example omp_schedule_prime.c
$ OMP_NUM_THREADS=4 ./example
```

N	Pi(N)	Default Time	Static Time	Dynamic Time	Guided Time
1024	172	0.000182	0.000120	0.000104	0.000121
2048	309	0.000561	0.000359	0.000425	0.000393
4096	564	0.001987	0.001309	0.001216	0.001239
8192	1028	0.007116	0.004474	0.004375	0.005114
16384	1900	0.029730	0.015594	0.015902	0.015161
32768	3512	0.099248	0.058475	0.056940	0.057160
65536	6542	0.358250	0.218291	0.244626	0.254815
131072	12251	1.416871	0.848736	0.788619	0.819390
262144	23000	5.207946	3.193940	3.062080	3.064527
524288	43390	20.565462	12.638959	12.086839	12.102800

Example: Triangular Loop

```
#pragma omp parallel shared(a, n)
{
  #pragma omp for
  for (int i = 0; i < n; ++i) {
    a[i] = 0.0;

    for (int j = 0; j < i; ++j) {
      a[i] += cos( -3.1 * sin( 2.3 * cos ( (double) j ))) ;
    }
  }
}
```

Example: Triangular Loop

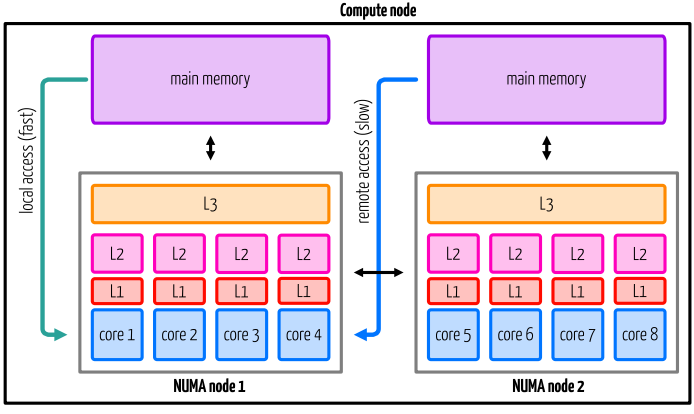
```
$ gcc -fopenmp -o example omp_schedule_triangular.c
$ OMP_NUM_THREADS=4 ./example
```

N	Default Time	Static Time	Dynamic Time	Guided Time
1024	0.025865	0.016811	0.018739	0.018241
2048	0.100062	0.070023	0.082587	0.091206
4096	0.383107	0.238520	0.232556	0.226914
8192	1.515341	0.905186	0.895541	0.880046
16384	6.064787	3.540685	3.526388	3.590453
32768	24.041088	15.465762	14.088137	14.539937
65536	97.495829	59.291353	59.403173	60.252156

OpenMP and NUMA

NUMA

Non-uniform memory access (NUMA) is a memory design where the memory access time depends on the memory location relative to the NUMA node



- access to the memory within the same NUMA node is faster (local access)
- access to the memory outside of the NUMA node is slower (remote access)

OpenMP and cc-NUMA

```
double* A = (double*)malloc(N * sizeof(double));

#pragma omp parallel for
for (int i = 0; i < N; i++) {
  A[i] = 0.0;
}
```

- For a serial code: all array elements are allocated in the memory of the NUMA node containing the core executing the thread
- For a parallel code on an OS with a first touch policy the array elements are allocated in the memory of the NUMA node containing the core executing the thread initializing

OpenMP and cc-NUMA

You also have two options for the placement of your threads. The first is put the threads far apart, i.e. on different sockets.

- may improve the aggregated memory bandwidth available to your application
- may improve the combined cache size available to your application
- may decrease performance of synchronization constructs

The second option is to put the threads close together, i.e. on two adjacent cores.

- may improve performance of synchronization constructs
- may decrease the available memory bandwidth and cache size

OpenMP and cc-NUMA

For the placement, you can use the `OMP_PROC_BIND` environment variable with the values:

- `close` : successively through the available places
- `spread` : which spreads the threads over the places

The second option is the `OMP_PLACES` environment variable with the values:

- `core` : places correspond to the cores
- `socket` : places correspond to the sockets

False Sharing

False Sharing in Action

Another thing you need to consider if you want to get the best out of OpenMP is false sharing. To discuss this we will start with this piece of code:

```
double local_sum[omp_get_max_threads()];
double sum = 0.0;

#pragma omp parallel shared(sum)
{
  int tid = omp_get_thread_num();
  local_sum[tid] = 0.0;

  #pragma omp omp for
  for (int i = 0; i < n; ++i)
      local_sum[tid] += 0.5 * x[i] + y[i];

  #pragma omp atomic
  sum += local_sum[tid];
}
```

False Sharing in Action

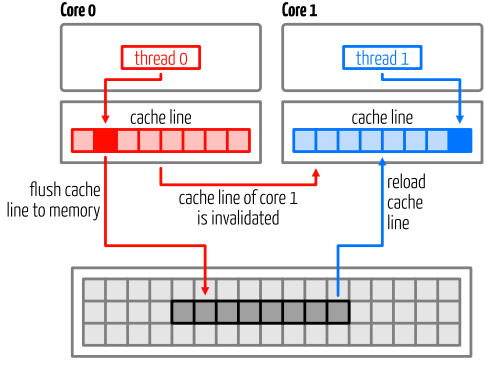
Let's measure the time spend in the parallel region (using the `omp_get_wtime()` function).

Threads	Time (s)
1	0.535418
2	0.421140
4	0.554419
8	0.597622

- The speedup from 1 thread to 2 threads is bad
- When going to 4 and 8 threads the time spend in the parallel region is worse than with 1 thread

False Sharing

False sharing is when threads impact the performance of each other while modifying independent variables sharing the same cache line



- If one core writes, the cache line holding the memory line is invalidated on other cores.
- Even though another core is not using that data, the second core will need to reload the line before it can access its own data again.

False Sharing: Solution

Solution: introduce a padding.

```
double local_sum[LINESIZE*omp_get_max_threads()];
double sum = 0.0;

#pragma omp parallel shared(sum)
{
  int tid = omp_get_thread_num();
  local_sum[LINESIZE*tid] = 0.0;

  #pragma omp omp for
  for (int i = 0; i < n; ++i)
      local_sum[LINESIZE*tid] += 0.5 * x[i] + y[i];

  #pragma omp atomic
  sum += local_sum[LINESIZE*tid];
}
```

False Sharing: Solution

Timing for different padding on a CPU with a cache line size of 64 bytes.

Threads	Time (s) padding = 4	Time (s) padding = 8	Time (s) padding = 16
1	0.535418	0.535418	0.535418
2	0.601417	0.270089	0.270843
4	0.441149	0.152651	0.149363

False sharing

- When threads access global or dynamically allocated shared data structures there is a potential source of false sharing
- False sharing may be difficult to spot. For example, when threads access completely different global variables that happen to be relatively close together in memory.
- Use thread-local copies of data when possible. The thread-local copy can be read and frequently modified and only when complete, be copied back to the global data structure