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## OpenMP

Parallelism within nodes

# Learning Objectives

- Describe the features of OpenMP and its parallelization strategy
- Create simple programs in C that demonstrate OpenMP features
- Parallelize smaller sections of existing code using OpenMP

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# Motivation

- Problems exist where Shared-Memory is required or beneficial
- The development of dedicated share-memory architectures is still ongoing
- The number of processors for such systems continuously increases
- But hardware-specific code is not portable
- MPI might be too difficult

# OpenMP

## Open Specifications for Multi Processing



- Consists of
  - ▶ Specification of pragmas (Hints) for the compiler describing parallelizable sections
  - ▶ Lightweight API to inquire and control parallelization
  - ▶ Compiler extension that translates code into parallelized (multi-threaded) version
- Therefore, a bit different everywhere
- Specified for Fortran and C
  - ▶ Also works with C++

# OpenMP

## Not a Magic Spell

- Meant for Shared Memory Systems
- Can be combined with MPI
- Does no magic! You have to
  - ▶ Sync IO access on your own
  - ▶ Lock memory on your own
  - ▶ Avoid deadlocks on your own
- Latest specification:  
OpenMP 6.0 from November 2024

# OpenMP Components

## ■ The C-API consists of 3 parts

### ▶ Compiler Directives

```
#pragma omp parallel default(shared) private(beta,pi)
```

### ▶ A Library

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

```
int omp_get_num_threads(void)
```

### ▶ Environmental Variables

```
export OMP_NUM_THREADS=8
```

## ■ Compile with:

```
▶ gcc -fopenmp foobar.c
```

```
▶ icc -no-multibyte-chars -qopenmp foobar.c
```

# Hello World

hello-openmp.c

```
#include <omp.h>

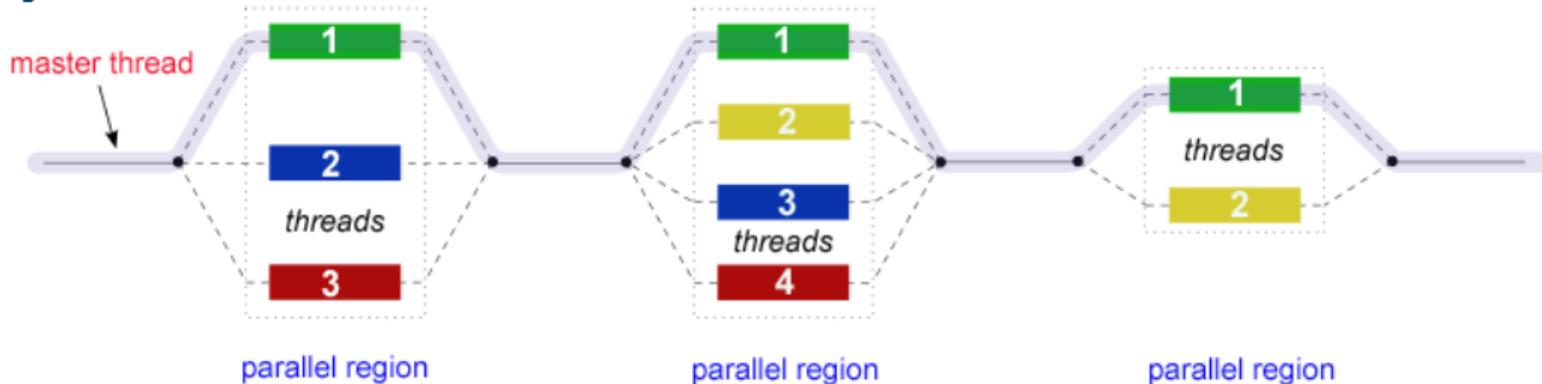
main () {
    #pragma omp parallel
    printf("Hello World");
}
```

Output

```
$ ./hello-openmp

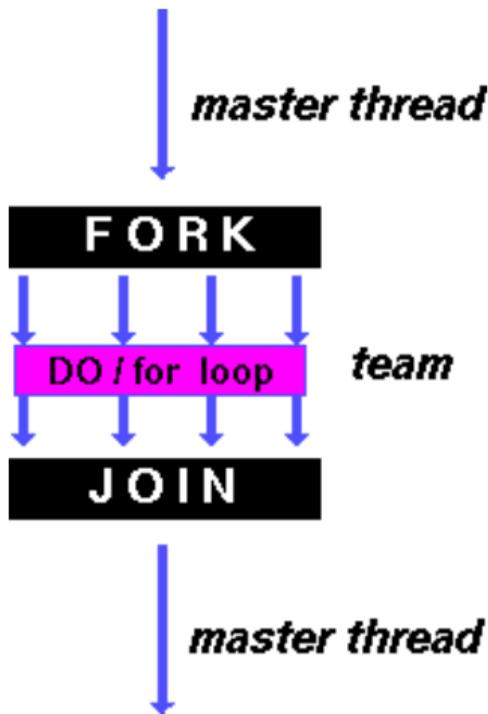
Hello World
Hello World
Hello World
Hello World
```

# Fork-Join Model



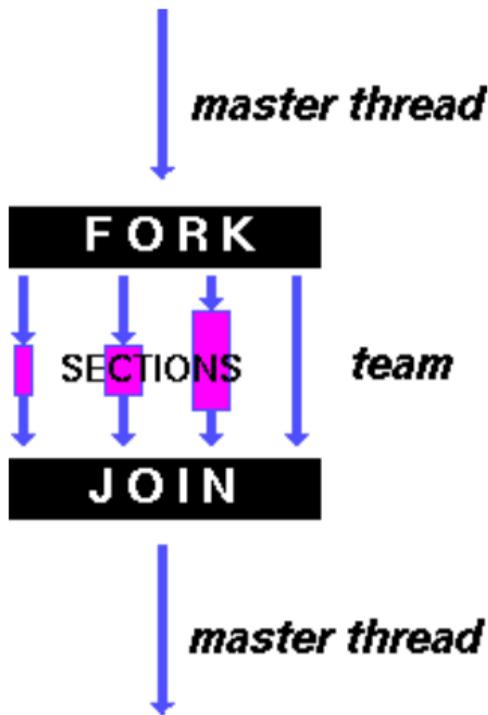
- Start with a single thread
  - ▶ *Master thread*
  - ▶ *or thread 0*
- More threads created at runtime
- Barrier at the end of parallel region
  - ▶ Additional threads are closed
  - ▶ Master thread continues

# Work Sharing I



- Single Instruction Multiple Data (SIMD)
- Example:
  - ▶ Add fixed number to vector
- Easy to parallelize

## Work Sharing II



- Multiple Instructions Multiple Data (MIMD)
- Different tasks (and code!) for different threads in the parallel section
- Hard to parallelize

# Communication and Data Space I

- Communication via Shared Variables
- Master thread
  - ▶ Execution context during entire runtime
- Worker threads
  - ▶ Execution context only during parallel regions

# Communication and Data Space II

- Variables are categorized in
  - ▶ *Shared*
  - ▶ *Private*
- Default is *Shared*
  - ▶ Good practice to always specify
- Simplifies coding special attributes
  - ▶ e.g., *Reduction*

# Communication and Data Space III

## ■ Shared variables

- ▶ All threads access same memory address
- ▶ Common way to communicate

## ■ Private variables

- ▶ One copy for each thread
- ▶ Value **undefined** at beginning and end of parallel region

# Synchronization

When using shared variables

- Avoid concurrent writes!
- One thread might read while another writes
- State at end of parallel region unclear
- Memory cache can be used to avoid conflicts
  - ▶ *Flush*-directive synchronizes memory

## Multiple Threads Example

thread-number.c

```
#include <omp.h>
main () {
    int nthreads, tid;
    /* do something in parallel: */
    #pragma omp parallel private(tid)
    {
        /* Obtain and print thread id */ tid = omp_get_thread_num();
        printf("Hello World from thread = %d\n", tid);
        /* Only master thread does this */ if (tid == 0)
        {
            nthreads = omp_get_num_threads();
            printf("Number of threads = %d\n", nthreads);
        }
    } /* All threads join master thread and terminate */
}
```

## Omp Directives Example

omp-directives.c

```
/* Some initializations */
for (i=0; i < N; i++)
    a[i] = b[i] = i * 1.0;

#pragma omp parallel shared(a,b,c) private(i)
{
    #pragma omp for schedule(dynamic)
    for (i=0; i < N; i++) { c[i] = a[i] + b[i]; }
} /* end of parallel section */

/* only the master does printf */
#pragma omp master
{
    for(i=0;i<N;i++) {printf("c[%d] = %f\n",i,c[i]);}
}
```

# Omp Directives

- *schedule* - defines how to distribute tasks  
Scheduler: static/dynamic/guided/runtime/auto
- *nowait* - Do not synchronize threads afterward (e.g., flush)
- *ordered* - Iterations must be done in the same order as in serial

omp-ordered.c

```
#pragma omp parallel for ordered  
for (i=0; i < N; i++){  
    // do heavy stuff  
  
    #pragma omp ordered  
    c[i] = a[i] + b[i];  
  
    // more heavy stuff  
} /* end of parallel section */
```

# OpenMp Directives

## ■ Parallization

- ▶ *for*
- ▶ *parallel*
- ▶ *sections*
- ▶ *single*
- ▶ *task*
- ▶ ...

## ■ Synchronization

- ▶ *barrier*
- ▶ *critical*
- ▶ *master*
- ▶ *atomic*
- ▶ ...

## ■ Data space

- ▶ *threadprivate*

# Directives Syntax

C/C++

```
#pragma omp directive [clause [[,] clause ...] ...]  
//Structured Block
```

Fortran

```
!$OMP directive [clause[[,] clause ...] ...]  
! Structured Block  
!$OMP END
```

## Important Clauses for Data Space

`#pragma omp parallel ...`

- `private (var1,var2,var3)`

- `shared (var1,var2,var3)`

- `default (shared/none)`

  - ▶ `private` is not allowed here!

- `reduction (operator:var1)`

  - ▶ `var1` is (implicitly) thread private and aggregated via operator at the end

omp-clauses.c

```
#pragma omp parallel default(shared) private(i) reduction(+:result)
{
    #pragma omp for schedule(static,chunk)
    for (i=0; i < n; i++)
        result = result + (a[i] * b[i]);
} // end omp parallel
printf("Final result= %f\n",result);
```

# Undefined Variables

- *private* variables
  - ▶ Undefined at start and end of parallel region
- *firstprivate(list of variables)*
  - ▶ Initializes *private* variables with value prior to region

# Important Library Functions

- `omp_in_parallel()`
- `omp_get_num_threads()`
- `omp_get_thread_num()`
- `omp_set_num_threads()`
- `omp_get_num_procs()`
- `omp_get_wtime()`
- `omp_get_wtick()`
- `omp_init_lock()`
- `omp_set_lock()`
- `omp_unset_lock()`
- `omp_test_lock()`
- `omp_destroy_lock()`

## Time Measurement

```
double omp_get_wtime(void);
```

- Returns time in seconds since a fixed arbitrary time in the past
- Temporal resolution may be limited due to OS architecture
- Elapsed time calculated as difference between two calls

timing.c

```
#pragma omp parallel
{
  // ...
  #pragma omp single nowait
  start = omp_get_wtime();
  // ... code of interest
  #pragma omp single nowait
  end = omp_get_wtime();
  // ...
} // end of parallel section
printf("time in seconds: %lf\n", end - start);
```

# OpenMP Loop Parallelization I

- Strength of OpenMP!
- Each thread handles a subset of iterations
- Should be SIMD - Beware of dependencies
- Clauses: Schedule, Order, ...

```
C  
  
#pragma omp for (+clauses)  
for(...)
```

- Only affects directly subsequent for loop

## OpenMP Loop Parallelization II

- *omp parallel* - Create parallel section
- *omp for* - Use existing threads to process loop
  - ▶ Must be in *omp parallel* region
  - ▶ Only affects the very next for loop
- *omp parallel for* - Both in one line

c

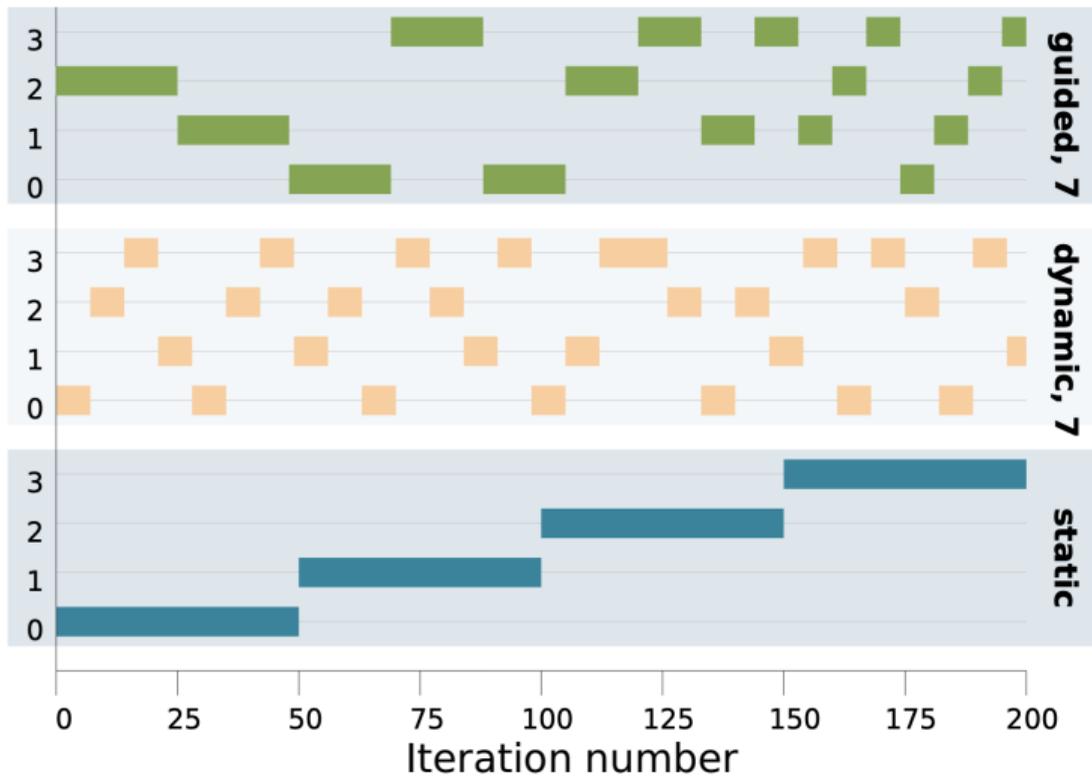
```
#pragma omp parallel for collapse(3) // collapse will flatten multiple loops
for(int l=0; l<10; ++l) {
    /* no code allowed here */
    for(int j=0; j<4; ++j) {
        /* no code allowed here */
        for(int k=0; k<5; ++k){
            foo[l][j][k] = 0;
        }
    }
}
```

# OpenMP Loop Parallelization III

- *omp parallel for ordered*
  - ▶ Threads process for loop iterations ordered as if sequentially
- *omp parallel for schedule*
  - ▶ Hint how iterations should be distributed among threads
  - ▶ *static* - Same chunk size
  - ▶ *dynamic* - Give out chunks on request (controlled with *chunk*)
  - ▶ *guided* - Chunk size decreases with iterations
  - ▶ *runtime* - Using environmental variables
  - ▶ *auto* - Let compiler and runtime decide

# Loop Scheduling

Thread id



# Parallel Sections

- Useful for MIMD operations
- *omp parallel sections* - to start several regions
  - ▶ Otherwise *omp section* for each region
- Each section is executed by one thread!
- Good for small tasks
- Order of execution is not defined

## Parallel Sections Example

parallel-sections.c

```
for (i=0; i < N; i++) {
    a[i] = i * 1.5;  b[i] = i + 22.35;
}
#pragma omp parallel shared(a,b,c,d) private(i)
{
    #pragma omp sections          // you might use "nowait"
    {
        #pragma omp section
        for (i=0; i < N; i++)
            c[i] = a[i] + b[i];
        #pragma omp section
        for (i=0; i < N; i++)
            d[i] = a[i] * b[i];
    } /* end of sections */
} /* end of parallel section */
```

# Important Directives

## #pragma omp directive

- *master* - Only executed by master thread
- *critical* - Only one thread allowed at a time
- *barrier* - Wait for all threads to reach this point
- *flush* - Synchronize shared memory of all threads
  - ▶ Implicitly done at *barrier*, *for*, *critical*, *parallel* ...

## Other Workload Distribution

- *omp single* - Only one thread executes block, used in parallel section
  - ▶ Useful for I/O operations
- *omp critical* - Only one thread at a time executes block
  - ▶ Useful to avoid data races
- *nowait* - Allow threads to pass by without waiting on each other

## Code within/without Parallel Sections I

parallel-1.c

```
int my_start, my_end;

void work(){
    /* my_start and my_end are undefined, because it's trying */
    /* to pull from global scope and private vars are undefined in that scope */
    printf("My subarray is from %d to %d\n", my_start, my_end);
}

int main(int argc, char* argv[]){
    #pragma omp parallel private(my_start, my_end)
    {
        /* get subarray indices */
        my_start = get_my_start(omp_get_thread_num(), omp_get_num_threads());
        my_end = get_my_end(omp_get_thread_num(), omp_get_num_threads());
        work();
    }
}
```

# Code within/without Parallel Sections II

## Solution 1: Variables as parameters

parallel-2.c

```
int my_start, my_end;

void work(int my_start, int my_end){
    printf("My subarray is from %d to %d\n", my_start, my_end);
}

int main(int argc, char* argv[]){
    #pragma omp parallel private(my_start, my_end)
    {
        /* get subarray indices */
        my_start = get_my_start(omp_get_thread_num(), omp_get_num_threads());
        my_end = get_my_end(omp_get_thread_num(), omp_get_num_threads());
        work(my_start, my_end);
    }
}
```

# Code within/without Parallel Sections III

## Solution 2: Using *omp threadprivate*

parallel-3.c

```
int my_start, my_end;
#pragma omp threadprivate(my_start, my_end)
void work(){
    printf("My subarray is from %d to %d\n", my_start, my_end);
}
int main(int argc, char* argv[]){
    #pragma omp parallel
    {
        /* get subarray indices */
        my_start = get_my_start(omp_get_thread_num(), omp_get_num_threads());
        my_end = get_my_end(omp_get_thread_num(), omp_get_num_threads());
        work();
    }
}
```

# Exercise

- Simple to more complex tasks
- Use the online OpenMP specification!
- Questions without coding are to test your understanding
- Use OpenMP for more problems
  - ▶ e.g., Calculate  $\pi$

# References

- <https://sourceware.org/gdb/current/onlinedocs/gdb/Threads.html>
- <https://www.openmp.org/spec-html/5.2/openmp.html>
- <https://gcc.gnu.org/onlinedocs/gcc/Optimize-Options.html>
- <https://gcc.gnu.org/wiki/Graphite/Parallelization>  
<https://hpc-tutorials.llnl.gov/openmp/>