Shared-Memory Programming: OpenMP

National Tsing Hua University

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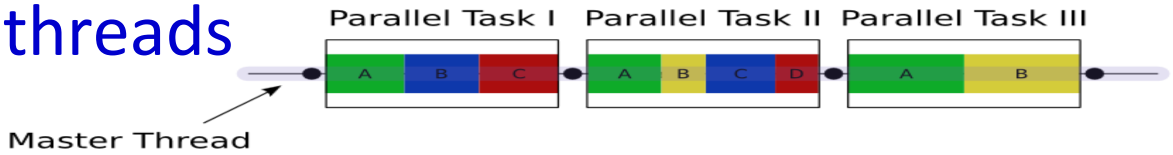
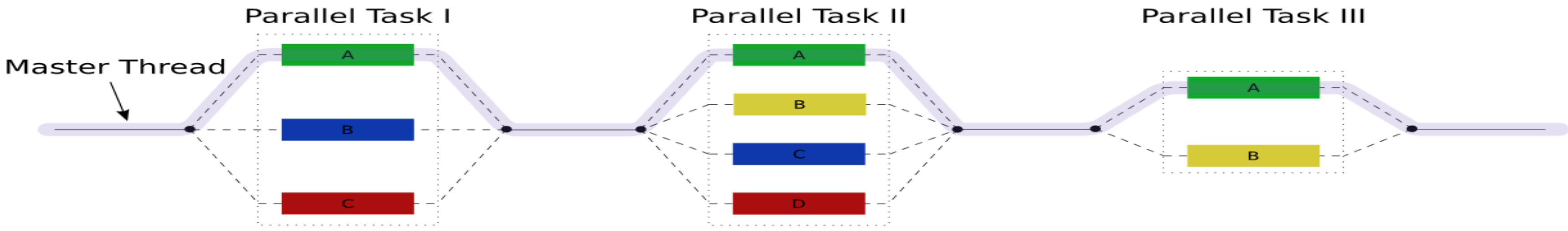
What's OpenMP

OpenMP == Open specification for **M**ulti-**P**rocessing

- An **API** : multi-threaded, shared memory parallelism
- **Portable**: the API is specified for C/C++ and Fortran
- **Fork-Join model**: the master thread forks a specified number of slave threads and divides task among them
- **Compiler Directive** Based: **Compiler** takes care of generating code that forks/joins threads and divide tasks to threads





Example

- Add two data arrays in parallel by specifying compiler directives:
  - Slave threads are forked and each thread works on different iterations

```
#include <omp.h>
// Serial code
int A[10], B[10], C[10];

// Beginning of parallel section. Fork a team of threads.
#pragma omp parallel for num_threads(10)
{
for (int i=0; i<10; i++)
   A[i] = B[i] + C[i];
} /* All threads join master thread and terminate */
```

OpenMP Directives

- C/C++ Format:

#pragma omp	directive-name	[clause, ...]	newline
Required.	Valid OpenMP directive: **parallel, do, for**	**Optional**. Clauses can be in any order, and repeated as necessary.	Required.

- Example:
  - #pragma omp parallel default(shared) private(beta,pi)

    parallel → directive-name; default(shared) → clause; private(beta,pi) → clause

- General Rules:
  - **Case sensitive**
  - Only one directive-name may be specified per directive
  - Each directive applies to at most one succeeding statement, which must be a structured block

OpenMP Outline

- Parallel Region Construct
  - Parallel Directive
- Working-Sharing Construct
  - DO/for Directive
  - SECTIONS Directive
  - SINGLE Directive
- Synchronization Construct
- Data Scope Attribute Clauses
- Run-Time Library Routines

Parallel Region Constructs --- Parallel Directive

- A parallel region is a block of code executed by multiple threads

```
#pragma omp parallel [clause ......]
                     if (scalar_expression)
                     num_threads (integer-expression)
structured_block
```

- Overview:
  - When **PARALLEL** is reached, a team of threads is created
  - The parallel region code is duplicated and executed by all threads
  - There is an implied barrier at the end of a parallel section.
  - One thread terminates, all threads terminate
- Limitations:
  - A parallel region must be a structured block that does not span multiple routines or code files
  - It is illegal to branch (goto) into or out of a parallel region, but you could call other functions within a parallel region

Parallel Region --- How Many Threads

- The number of threads in a parallel region is determined in order of following precedence:
  - Evaluation of the **IF** clause
    - If FALSE, it is executed serially by the master thread
    - E.g: #pragma omp parallel IF(para == true)
  - Setting of the **num_threads** clause
    - E.g.: #pragma omp parallel num_threads(10)
  - Use of the **omp_set_num_threads()** library function
    - Called **BEFORE** the parallel region
  - Setting of the **OMP_NUM_THREADS** environment variable
    - Called **BEFORE** the parallel region
  - By default - usually the number of CPUs on a node

Nested Parallel Region

```
// A total of 6 “hello world!” is printed
#pragma omp parallel num_threads(2)
{
   #pragma omp parallel num_threads(3)
   {
            printf(“hello world!”);
   }
}
```

- check if nested parallel regions are enabled
  - **omp_get_nested ()**
- To disable/enable nested parallel regions:
  - **omp_set_nested (bool)**
  - Setting of the **OMP_NESTED** environment variable
- If nested is not supported or enabled:
  - Only one thread is created for the nested parallel region code

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Work-Sharing Constructs

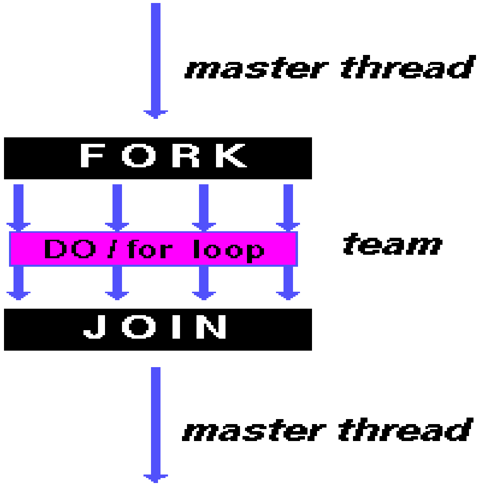
- Definition:
  - A work-sharing construct divides the execution of the enclosed code region among the threads that encounter it
  - Work-sharing constructs **DO NOT** launch new threads
  - There is no implied barrier upon entry to a work-sharing construct, however there is an implied **barrier at the end** of a work sharing construct

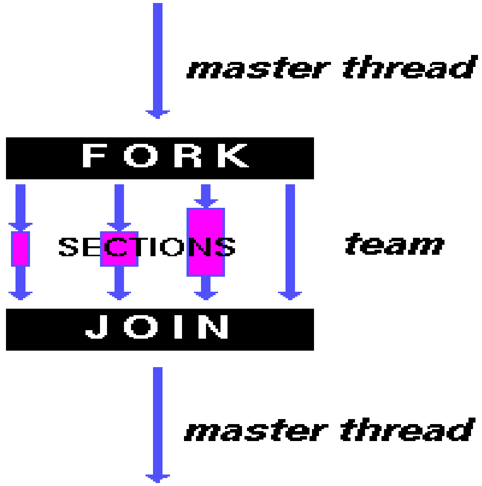
Type of Work-Sharing Constructs

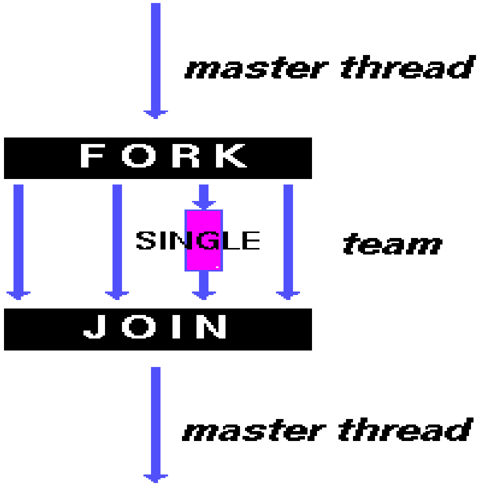
DO / for - shares iterations of a loop across the team. Represents a type of "data parallelism".

SECTIONS - breaks work into separate, discrete sections of code. Each section is executed by a thread.

SINGLE - serializes a section of code by running with a single thread.







- Notice:
  - should be enclosed within a **parallel region** for parallelism

DO / for Directive

- Purpose: indicate the iterations of the loop immediately following it must be executed in parallel by the team of threads

```
#pragma omp for [clause ......]
                    schedule (type [,chunk])
                    ordered
                    nowait
                    collapse (n)
for_loop
```

- Do/for Directive Specific Clauses:
  - **nowait:** Do not synchronize threads at the end of the loop
  - **schedule:** Describes how iterations are divided among threads
  - **ordered**: Iterations must be executed as in a serial program
  - **collapse**: Specifies how many loops in a nested loop should be collapsed into one large iteration space and divided according to the schedule clause

DO / for Directive --- Schedule Clause

- **STATIC**
  - Loop iterations are divided into ***chunks***
  - If chunk is not specified, the iterations are evenly (if possible) divided contiguously among the threads
  - Then statically assigned to threads
- **DYNAMIC:** When a thread finishes one **chunk** **(default size: 1)**, it is dynamically assigned another
- **GUIDED:** Similar to DYNAMIC except **chunk size decreases over time** (better load balancing)
- **RUNTIME:** The scheduling decision is deferred until runtime by the environment variable **OMP_SCHEDULE**
- **AUTO:** The scheduling decision is delegated to the compiler and/or runtime system

Scheduling Examples

- A for loop with 100 iterations and 4 threads:
  - schedule(static, 10)
    - Thread0: Iter0-10, Iter40-50, Iter80-90
    - Thread0: Iter10-20, Iter50-60, Iter90-100
    - Thread0: Iter20-30, Iter60-70
    - Thread0: Iter30-40, Iter70-80
  - schedule(dynamic, 10)
    - Thread0: Iter0-10, Iter70-80, Iter80-90, Iter90-100
    - Thread0: Iter10-20, Iter50-60
    - Thread0: Iter20-30, Iter60-70
    - Thread0: Iter30-40, Iter40-50

Scheduling Examples

- A for loop with 100 iterations and 4 threads:
  - schedule(guided, 10)
    - Thread0: Iter0-10, Iter40-50, Iter80-85
    - Thread0: Iter10-20, Iter50-60, Iter85-90
    - Thread0: Iter20-30, Iter60-70, Iter90-95
    - Thread0: Iter30-40, Iter70-80, Iter95-100

DO / for Directive --- Example

```
#include <omp.h>
#define NUM_THREAD 2
#define CHUNKSIZE 100
#define N 1000
main () {
   int a[N], b[N], c[N];
   /* Some initializations */
   for (int i=0; i < N; i++) a[i] = b[i] = i;
   int chunk = CHUNKSIZE;
   int thread = NUM_THREAD;

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

Shared variables among threads

Private variables of each thread

DO / for Directive --- Order

```
#pragma omp parallel for
for (int i = 0; i < 10; i++)
   printf("i=%d, thread = %d\n",
             i, omp_get_thread_num());
```

```
#pragma omp parallel for order
for (int i = 0; i < 3; i++)
   printf("i=%d, thread = %d\n",
             i, omp_get_thread_num());
```

```
i=2, thread = 0
i=0, thread = 1
i=1, thread = 2
i=3, thread = 1
i=4, thread = 0
i=8, thread = 2
i=5, thread = 1
i=6, thread = 2
i=9, thread = 1
i=7, thread = 1
```

```
i=0, thread = 0
i=1, thread = 1
i=2, thread = 2
i=3, thread = 1
i=4, thread = 0
i=5, thread = 2
i=6, thread = 1
i=7, thread = 2
i=8, thread = 1
i=9, thread = 1
```

DO / for Directive --- Collapse

```
#pragma omp parallel num_thread(6)
#pragma omp for schedule(dynamic)
for (int i = 0; i < 3; i++)
    for (int j = 0; j < 3; j++)
        printf("i=%d, j=%d, thread = %d\n",
                    i, j, omp_get_thread_num());
```

```
#pragma omp parallel num_thread(6)
#pragma omp for schedule(dynamic)
                                    collapse(2)
for (int i = 0; i < 3; i++)
    for (int j = 0; j < 3; j++)
        printf("i=%d, j=%d, thread = %d\n",
                    i, j, omp_get_thread_num());
```

```
i=1, j=0, thread = 1
i=2, j=0, thread = 2
i=0, j=0, thread = 0
i=1, j=1, thread = 1
i=2, j=1, thread = 2
i=0, j=1, thread = 0
i=1, j=2, thread = 1
i=2, j=2, thread = 2
i=0, j=2, thread = 0
```

```
i=0, j=0, thread = 0
i=0, j=2, thread = 1
i=1, j=0, thread = 2
i=2, j=0, thread = 4
i=0, j=1, thread = 0
i=1, j=2, thread = 3
i=2, j=2, thread = 5
i=1, j=1, thread = 2
i=2, j=1, thread = 4
```

SECTIONS Directive

- A non-iterative work-sharing construct
- It specifies that the enclosed section(s) of **CODE** are to be divided among the threads in the team
- Independent **SECTION** directives are nested within a **SECTIONS** directive
- Each SECTION is executed **ONCE** by **ONE** thread
- The mapping between threads and sections is decided by the **library implementation**

```
#pragma omp sections [clause ......]
{
  #pragma omp section
        structured_block

  #pragma omp section
        structured_block
}
```

SECTIONS Directive --- Example

```
int N = 1000
int a[N], b[N], c[N], d[N];

#pragma omp parallel num_thread(2) shared(a,b,c,d) private(i)
{
   #pragma omp sections          /* specify sections*/
    {
        #pragma omp section   /* 1st section*/
         {
               for (int i=0; i < N; i++) c[i] = a[i] + b[i];
         }
        #pragma omp section   /* 2nd  section*/
         {
               for (int i=0; i < N; i++) d[i] = a[i] + b[i];
         }
    } /* end of section */
}   /* end of parallel section */
```

SINGLE Directive

- The SINGLE directive specifies that the enclosed code is to be executed by only one thread in the team.
- May be useful when dealing with sections of code that are not thread safe (such as I/O)
- Threads in the team that do not execute the SINGLE directive, wait at the end of the enclosed code block, unless a **nowait** clause is specified
- Example:

```
int input;
#pragma omp parallel num_thread(10)  shared(input)
{
    // computing code that can be prcessed in parallel
    #pragma omp single      /* specify section
    {
        scanf("%d", &input);
    } /* end of seralized I/O call */

    printf("input is %d", input);
}   /* end of parallel section */
```

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Synchronization Constructs

- For synchronization purpose among threads

```
#pragma omp [synchronization_directive] [clause ......]
structured_block
```

- Synchronization Directives
  - **master**: only executed by the **master** thread
    - No implicit barrier at the end
    - More efficient than SINGLE directive
  - **critical**: must be executed by only **one** thread at a time
    - Threads will be blocked until the critical section is clear
  - **barrier**: blocked until **all** threads reach the call
  - **atomic**: **memory** location must be **updated** atomically
    - provide a mini-critical section

LOCK OpenMP Routine

- void omp_init_lock(omp_lock_t *lock)
  - Initializes a lock associated with the lock variable
- void omp_destroy_lock(omp_lock_t *lock)
  - Disassociates the given lock variable from any locks
- void omp_set_lock(omp_lock_t *lock)
  - Force the thread to wait until the specified lock is available
- void omp_unset_lock(omp_lock_t *lock)
  - Releases the lock from the executing subroutine
- int omp_test_lock(omp_lock_t *lock)
  - Attempts to set a lock, but does **NOT** block **if unavailable**

Example & Comparison

- Advantage of using critical over lock:
  - no need to declare, initialize and destroy a lock
  - you always have explicit control over where your critical section ends
  - Less overhead with compiler assist

```
#include <omp.h>
main () {
   int count=0;
   #pragma omp parallel
         #pragma omp critical
                  count++;
}
```

```
#include <omp.h>
main () {
   int count=0;
   omp_lock_t *lock;
   omp_init_lock(lock)
   #pragma omp parallel
     {
           omp_set_lock(lock);
           count++;
           omp_unset_lock(lock);
     }
     omp_destory_lock(lock)
}
```

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OpenMP Dat Scope

- This is critical to understand the scope of each data
  - OpenMP is based on shared memory programming model
  - Most variables are shared by default
- Global shared variables:
  - File scope variables, static
- Private non-shared variables:
  - Loop index variables
  - Stack variables in subroutines called from parallel regions
- Data scope can be explicitly defined by clauses…
  - PRIVATE , SHARED, FIRSTPRIVATE, LASTPRIVATE
  - DEFAULT, REDUCTION, COPYIN

Data Scope Attribute Clauses

- **PRIVATE** (var_list):
  - Declares variables in its list to be private to each thread; variable value is **NOT initialized & will not be maintained outside the parallel region**
- **SHARED** (var_list):
  - Declares variables in its list to be shared among all threads
  - By default, all variables in the work sharing region are shared except the loop iteration counter.
- **FIRSTPRIVATE** (var_list):
  - Same as **PRIVATE** clause, but the variable is **INITIALIZED** according to the value of their original objects prior to entry into the parallel region
- **LASTPRIVATE** (var_list)
  - Same as PRIVATE clause, with a copy from the **LAST** loop iteration or section to the original variable object

Examples

- firstprivate (var_list)

```
int var1 = 10;
#pragma omp parallel firstprivate (var1)
{
        printf("var1:%d" var1);
}
```

- lastprivate (var_list)

```
int var1 = 10;
#pragma omp parallel lastprivate (var1) num_thread(10)
{
        int id = omp_get_thread_num();
        sleep(id);
        var1=id;
}
printf("var1:%d", var1);
```

Data Scope Attribute Clauses

- DEFAULT (PRIVATE | FIRSTPRIVATE | SHARED | NONE)
  - Allows the user to specify a default scope for **ALL** variables in the parallel region
- COPYIN (var_list)
  - Assigning the same variable value based on the instance from the master thread
- COPYPRIVATE (var_list)
  - Broadcast values acquired by a single thread directly to all instances in the other thread
  - Associated with the **SINGLE** directive
- REDUCTION (operator: var_list)
  - **A private copy** for each list variable is **created for each thread**
  - Performs a reduction on all variable instances
  - Write the final result to the **global shared copy**

Reduction Clause Example

```
#include <omp.h>
main () {
   int i, n, chunk, a[100], b[100], result;
   n = 10; chunk = 2; result = 0;
   for (i=0; i < n; i++) a[i] = b[i] = I;

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

- Reduction operators:
  - +, *, &, |, ^, &&, ||

OpenMP Clause Summary

Clause	Directive			
	PARALLEL	DO/for	SECTIONS	SINGLE
IF	V			
PRIVATE	V	V	V	V
SHARED	V	V		
DEFAULT	V			
FIRSTPRIVATE	V	V	V	V
LASTPRIVATE		V	V	
REDUCTION	V	V	V	
COPYIN	V			
COPYPRIVATE				V
SCHEDULE		V		
ORDERED		V		
NOWAIT		V	V	

- **Synchronization** Directives **DO NOT** accept clauses

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Run-Time Library Routines

- void omp_set_num_threads(int num_threads)
  - Sets the number of threads that will be used in the next parallel region
- int omp_get_num_threads(void)
  - Returns the number of threads currently executing for the parallel region
- int omp_get_thread_num(void)
  - Returns the thread number of the thread, within the team, making this call
  - The master thread of the team is thread 0
- int omp_get_thread_limit (void)
  - Returns the maximum number of OpenMP threads available to a program
- int omp_get_num_procs(void)
  - Returns the number of processors that are available to the program
- int omp_in_parallel(void)
  - determine if the section of code which is executing is parallel or not

Many others are available for more complicated usage

Reference

- Textbook:
  - Parallel Computing Chap8
- openMP Tutorial
  - https://computing.llnl.gov/tutorials/openMP/
- openMP API
  - http://gcc.gnu.org/onlinedocs/libgomp.pdf