Parallel Programming Tutorial - More on OpenMP

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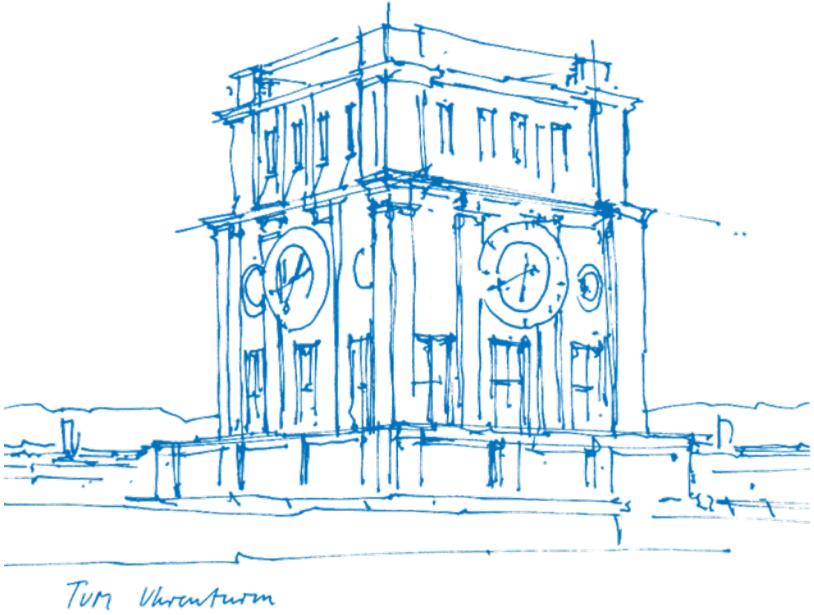


Organizational

- **Q&A Sessions**
  - Hands-on help with the assignments
  - First session on 31st May
  - Room : 01.06.020
  - Fridays 08:15 - 09:45

- **Guest Lecture on next Monday**
  - By Michael Klemm - Performance Engineer at Intel and CEO of the OpenMP ARB
  - Inner workings of the OpenMP ARB
  - (Mainly) How to utilize SIMD

Recap from last tutorial on OpenMP

Quiz; how to create a team of four threads to print their ids

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

int main(){

    int num_threads=4;
    omp_set_num_threads(num_threads);

    for (int i = 0; i < num_threads; i++)
    {
        std::cout << "My id is: "
                  << omp_get_thread_num() << std::endl;
    }
}
```

Quiz; how to create a team of four threads to print their ids

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

int main(){

    int num_threads=4;
    omp_set_num_threads(num_threads);

    for (int i = 0; i < num_threads; i++)
    {
        std::cout << "My id is: "
                  << omp_get_thread_num() << std::endl;
    }
}
```

./example1

My id is: 0
My id is: 0
My id is: 0
My id is: 0

Quiz (Cont.)

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

int main(){

    int num_threads=4;
    omp_set_num_threads(num_threads);

    #pragma omp for
    for (int i = 0; i < num_threads; i++)
    {
        std::cout << "My id is: "
                  << omp_get_thread_num() << std::endl;
    }
}
```

Quiz (Cont.)

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

int main(){

    int num_threads=4;
    omp_set_num_threads(num_threads);

    #pragma omp for
    for (int i = 0; i < num_threads; i++)
    {
        std::cout << "My id is: "
                  << omp_get_thread_num() << std::endl;
    }
}
```

./example2

My id is: 0
My id is: 0
My id is: 0
My id is: 0

Quiz (Cont.)

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

int main(){

    int num_threads=4;
    omp_set_num_threads(num_threads);

    #pragma omp parallel
    {
        for (int i = 0; i < num_threads; i++)
        {
            #pragma omp critical
            std::cout << "My id is: "
                      << omp_get_thread_num() << std::endl;
        }
    }
}
```

Quiz (Cont.)

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

int main(){

    int num_threads=4;
    omp_set_num_threads(num_threads);

    #pragma omp parallel
    {
        for (int i = 0; i < num_threads; i++)
        {
            #pragma omp critical
            std::cout << "My id is: "
                      << omp_get_thread_num() << std::endl;
        }
    }
}
```

./example3

My id is: 3
My id is: 0
My id is: 3
My id is: 0
My id is: 3
My id is: 0
My id is: 3
My id is: 0
My id is: 1
My id is: 1
My id is: 1
My id is: 1
My id is: 2
My id is: 2
My id is: 2
My id is: 2

Quiz (Cont.)

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

int main(){

    int num_threads=4;
    omp_set_num_threads(num_threads);

    #pragma omp parallel
    {
        #pragma omp parallel for
        for (int i = 0; i < num_threads; i++)
        {
            #pragma omp critical
            std::cout << "My id is: "
                      << omp_get_thread_num() << std::endl;
        }
    }
}
```

Quiz (Cont.)

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

int main(){

    int num_threads=4;
    omp_set_num_threads(num_threads);

    #pragma omp parallel
    {
        #pragma omp parallel for
        for (int i = 0; i < num_threads; i++)
        {
            #pragma omp critical
            std::cout << "My id is: "
                      << omp_get_thread_num() << std::endl;
        }
    }
}
```

./example4

My id is: 0
My id is: 0
My id is: 0
My id is: 0
My id is: 0
My id is: 0
My id is: 0
My id is: 0
My id is: 0
My id is: 0
My id is: 0
My id is: 0
My id is: 0
My id is: 0
My id is: 0
My id is: 0

Quiz (Cont.)

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

int main(){

    int num_threads=4;
    omp_set_num_threads(num_threads);
    omp_set_nested(1);

    #pragma omp parallel
    {
        #pragma omp parallel for
        for (int i = 0; i < num_threads; i++)
        {
            #pragma omp critical
            std::cout << "My id is: "
                      << omp_get_thread_num() << std::endl;
        }
    }
}
```

Quiz (Cont.)

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

int main(){

    int num_threads=4;
    omp_set_num_threads(num_threads);
    omp_set_nested(1);

    #pragma omp parallel
    {
        #pragma omp parallel for
        for (int i = 0; i < num_threads; i++)
        {
            #pragma omp critical
            std::cout << "My id is: "
                      << omp_get_thread_num() << std::endl;
        }
    }
}
```

./example5

My id is: 1
My id is: 0
My id is: 2
My id is: 3
My id is: 1
My id is: 2
My id is: 0
My id is: 1
My id is: 1
My id is: 0
My id is: 3
My id is: 2
My id is: 3
My id is: 0
My id is: 3
My id is: 2

Quiz (Cont.)

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

int main(){

    int num_threads=4;
    omp_set_num_threads(num_threads);

    #pragma omp parallel
    {
        #pragma omp for
        for (int i = 0; i < num_threads; i++)
        {
            #pragma omp critical
            std::cout << "My id is: "
                      << omp_get_thread_num() << std::endl;
        }
    }
}
```

./example6

My id is: 0
My id is: 1
My id is: 2
My id is: 3

Quiz (Cont.)

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

int main(){

    int num_threads=4;
    omp_set_num_threads(num_threads);

    #pragma omp parallel for
    for (int i = 0; i < num_threads; i++)
    {
        #pragma omp critical
        std::cout << "My id is: "
                  << omp_get_thread_num() << std::endl;
    }
}
```

./example7

My id is: 2
My id is: 0
My id is: 1
My id is: 3

OpenMP Sections

OpenMP Sections

```
#pragma omp sections <{clause, ...}>
{
   #pragma omp section
   <structured block>

   #pragma omp section
   <structured block>
}
```

- The sections directive contains a set of structured blocks that are executed by single threads of a team
- Each structured block is preceded by a section directive
- The scheduling of the sections is implementation defined
- There is an implicit barrier at the end of a sections directive (unless `nowait`)
- Clauses: `private`, `firstprivate`, `lastprivate`, `reduction(identifier)`, `nowait`

Nested Regions

```
// environmnet variable to set nested parallelism
OMP_NESTED
// library function to set/get nested parallelism
int omp_set_nested( int nested )
int omp_get_nested( void )
// limits/returns the number of maximal nested active parallel regions
int omp_set_max_active_levels( int max_levels )
int omp_get_max_active_levels( void )
// returns the number of current nesting level
int omp_get_level( void )
```

- Parallel regions and parallel sections may be arbitrarily nested inside each other
- If nested parallelism is disabled (default), the newly created team of threads will consist only of the encountering thread

Hint

- Take care of oversubscription when using nested parallelism.

Example: Traverse a binary tree

```
struct node
{
    struct node *left, *right;
    int key;
    node(int k):key(k){}
};

void traverse(struct node *p)
{
    if (p->left != NULL)
        traverse(p->left);

    if (p->right != NULL)
        traverse(p->right);

    process(p);
}
```

```
void process(struct node *p){
    usleep(1000000);
    std::cout << "element with key: "
              << p->key << " is processed"
              << std::endl;
}

int main(int argc, char *argv[])
{
    struct node *tree = new struct node(0);
    tree->left = new struct node(1);
    tree->right = new struct node(2);
    tree->left->left  = new struct node(3);
    tree->left->right = new struct node(4);
    tree->right->left  = new struct node(5);
    tree->right->right = new struct node(6);

    traverse(tree);
    return 0;
}
```

Example: Traverse a binary tree (Cont.)

```
void traverse(struct node *p)
{
    #pragma omp parallel
    {
        #pragma omp sections
        {

            #pragma omp section
            {
                if (p->left != NULL)
                    traverse(p->left);
            }

            #pragma omp section
            {
                if (p->right != NULL)
                    traverse(p->right);
            }
        }
    }
    process(p);
}
```

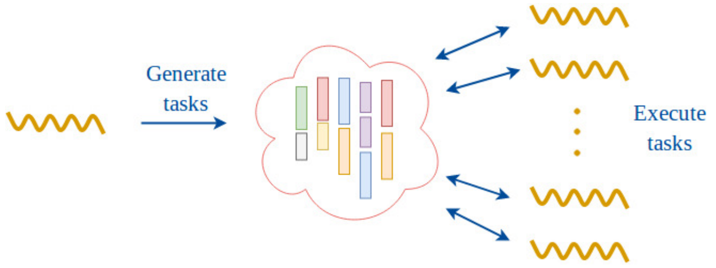
```
void process(struct node *p){
    usleep(1000000);
    #pragma omp critical
    std::cout << "element with key: "
              << p->key << " is processed"
              << std::endl;
}
int main(int argc, char *argv[])
{
    struct node *tree = new struct node(0);
    tree->left = new struct node(1);
    tree->right = new struct node(2);
    tree->left->left  = new struct node(3);
    tree->left->right = new struct node(4);
    tree->right->left  = new struct node(5);
    tree->right->right = new struct node(6);

    omp_set_nested(1);
    omp_set_max_active_levels(2);

    traverse(tree);
    return 0;
}
```

OpenMP Tasks

OpenMP Tasks

Why Tasks?

- We don't always deal with simple for loops for parallelization
- We don't always deal with simple data structures like arrays
- Some times we don't know the length of the loops at compile time e.g., while loop
- Some times we deal with unknown number of parallel sections
- We need to deal with parallelization of recursive algorithms
- It is possible without tasks (OpenMP 3.0) but it is not pretty



Task semantics

Terminology

task A specific instance of executable code and its data environment and ICVs.

task region A region consisting of all code encountered during the execution of a task.

explicit task A task generated when a `task` construct is encountered.

implicit task A task generated by an implicit parallel region.

tied task A task that, when its task region is suspended, can be resumed only by the same thread.

untied task A task that, when its task region is suspended, can be resumed by any thread in the team.

undeferred task A task for which execution is not deferred with respect to its generating task region.

included task A task for which execution is sequentially included in the generating task region.

merged task A task for which the data environment is the same as that of its generating task region.

Task semantics (Cont.)

```
#pragma omp task <{clause, ...}>
<structured block>
```

- Defines an explicit task, generated from the associated structured block.
- The encountering thread may immediately execute the task or defer it.
- Deferred tasks may be executed by any thread of the team.
- Tasks may be nested, but the task region of the inner task is not part of the task region of the outer task.
- A thread that encounters a task scheduling point (TSP) within a task may temporarily suspend this task.
- By default a task is tied to a thread (unless clause `untied`).

Task syntax

```
#pragma omp task <{clause, ...}>
<structured block>
```

Clauses (not exhaustive)

- `if (<scalar logical expression>)`
  if false, an undeferred task is generated
- `final (<scalar logical expression)`
  if true, the generated task and all child tasks are included (sequentialized) tasks
- `default (private | firstprivate | shared | none)`
  default is firstprivate for tasks
- `mergeable`
  if the generated task is an undeferred or included task, the generation may generate a merged task
- `private, firstprivate, shared ( <list> )`

Task Scheduling Points (TSPs)

```
#pragma omp taskyield
```

- Specifies that the current task can be suspended (implicit TSP)

```
#pragma omp taskwait
```

- Specifies a wait on the completion of child tasks of the current task (implict TSP)

```
#pragma omp taskgroup
```

- Specifies a wait on the completion of child tasks of the current task and their descendant tasks (implict TSP)

```
int omp_set_dynamic( int dynamic_threads )
```

- Enables or disables dynamic adjustment of number of threads available for tasks in subsequent parallel regions

Task Scheduling

Whenever a thread reaches a TSP, the implementation may perform a task switch, implied by the following locations:

- immediately following the generation of an explicit task
- after the completion of a task region
- in a taskyield region
- in a taskwait region
- at the end of a taskgroup region
- in an implicit or explicit barrier region
- ...

Example 1: Hello world using tasks

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

int main(int argc, char *argv[])
{
        #pragma omp parallel
        {
            #pragma omp task
            std::cout << "Hello World from task"
                      << std::endl;
        }
        return 0;
}
```

OMP_NUM_THREADS=4 ./example1

Hello World from task
Hello World from task
Hello World from task
Hello World from task

Example 2: Which threads execute the tasks

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

int main(int argc, char *argv[])
{
        #pragma omp parallel
        {
            #pragma omp task
            {
                #pragma omp critical
                std::cout << "Hello World from task,\
                  executed by thread: "
                          << omp_get_thread_num()
                          << std::endl;
            }
        }
        return 0;
}
```

OMP_NUM_THREADS=4 ./example2

Hello World from task, executed by thread: 0
Hello World from task, executed by thread: 3
Hello World from task, executed by thread: 2
Hello World from task, executed by thread: 1

or

Hello World from task, executed by thread: 0
Hello World from task, executed by thread: 1
Hello World from task, executed by thread: 2
Hello World from task, executed by thread: 0

or ...

Example 3: Using a single thread to create tasks

```
int main(int argc, char *argv[])
{
    #pragma omp parallel
    {
        #pragma omp single
        {
            for (int t = 0; t < omp_get_num_threads(); t++)
            {
                #pragma omp task
                {
                    #pragma omp critical
                    std::cout << "Hello World from task,\
                              executed by thread: "
                              << omp_get_thread_num()
                              << std::endl;
                }
            }
        }
    }
    return 0;
}
```

OMP_NUM_THREADS=4 ./example3

Hello World from task, executed by thread: 2
Hello World from task, executed by thread: 1
Hello World from task, executed by thread: 2
Hello World from task, executed by thread: 0

- Only one thread creates the tasks
- Unlike the previous example where all threads created tasks
- Created tasks can be nested and are scheduled to be executed by the available threads

Example 4: List traversal

```
void process_element(int &elem){
        usleep(1000000);
        std::cout << elem << std::endl;
}

void traverse_list(std::forward_list<int> &l){
        for (auto it = l.begin(); it != l.end() ; it++) {
                process_element(*it);
        }
}

int main(int argc, char *argv[])
{
        std::forward_list<int> l;
        l.assign({0,1,2,3,4,5,6,7,8,9});

        traverse_list(l);

        return 0;
}
```

time ./example4

0
1
2
3
4
5
6
7
8
9

real 0m10.006s

Example 4: List traversal (Cont.)

```
void process_element(int &elem){
        usleep(1000000);
        #pragma omp critical
        std::cout << elem << std::endl;
}

void traverse_list(std::forward_list<int> &l){
        #pragma omp parallel
        {
                #pragma omp single
                for (auto it = l.begin(); it != l.end() ; it++) {
                        #pragma omp task
                        process_element(*it);
                }
        }
}
```

time OMP_NUM_THREADS=4 ./example4

0
1
2
3
4
5
6
7
8
9

real 0m3.015s

Example 5: Fibonacci Number

```c
int fib(int n) {
    int i, j;

    if (n < 2) return n;

    i = fib(n - 1);
    j = fib(n - 2);

    return i + j;
}
```

```c
int main(int argc, char** argv) {
    int n = 30;

    if(argc > 1)
        n= atoi(argv[1]);

    printf("fib(%d) = %d\n", n, fib(n));

}
```

Example 5: Fibonacci Number (Cont.)

```c
int fib(int n) {
    int i, j;

    if (n < 2) return n;

    #pragma omp task shared(i) firstprivate(n)
    i = fib(n - 1);

    #pragma omp task shared(j) firstprivate(n)
    j = fib(n - 2);

    #pragma omp taskwait
    return i + j;
}
```

```c
int main(int argc, char** argv) {
    int n = 30;

    if(argc > 1)
        n= atoi(argv[1]);

    omp_set_num_threads(4);

    #pragma omp parallel shared(n)
    {
        #pragma omp single
        printf("fib(%d) = %d\n", n, fib(n));
    }
}
```

Example 5: Fibonacci Number, Runtime

```
$ time ./fib 35
fib(35) = 9227465

real    0m9.785s
user    0m25.933s
sys     0m0.000s
```

Example 5: Fibonacci Number, final task

```c
#define T 30 // THRESHOLD

int fib(int n)
{
    int i, j;

    if (n < 2)
        return n;

    #pragma omp task shared(i) firstprivate(n) final(n < T)
    i = fib(n - 1);

    #pragma omp task shared(j) firstprivate(n) final(n < T)
    j = fib(n - 2);

    #pragma omp taskwait
    return i + j;
}
```

Example 5: Fibonacci Number, Runtime Final (GCC)

```
$ time ./fib_final 35
fib(35) = 9227465

real    0m0.392s
user    0m0.800s
sys     0m0.000s
```

Other directives

```
#pragma omp single <{clause, ...}>
```

- The single directive specifies that the associated block is executed by only one thread (not necessarily the master)
- The other threads of the team wait at an implict barrier at the end of the single construct (unless `nowait`)
- Clauses: `private`, `firstprivate`, `nowait`

```
#pragma omp master <{clause, ...}>
```

- Same as single, but the thread is solely executed by the master thread
- Clauses: `private`, `firstprivate`, `nowait`

Other directives (Cont.)

```
#pragma omp critical [<name>]
```

- Restricts the execution of the associated structured block to a single thread at a time
- An optional name may be used to identify the critical construct
- All critical constructs without a name use a default name

```
#pragma omp barrier
```

- Specifies an explicit barrier
- All threads of a team must execute the barrier region
- Includes an implicit task scheduling point

Other directives (Cont.)

```
#pragma omp atomic [read | write | update | capture]
<expression>
```

Example

```
#pragma omp atomic write
x = 41;
#pragma omp atomic
{
  v = x;
  x++;
}
```

- Ensures that a specific storage location is accessed atomically
- The expression reads|writes|read-writes|(read-writes + updates other variable) the storage location
- The structured block has two consecutive expressions
- To avoid race conditions, all accesses to a shared storage location must be protected with an atomic construct

Assignment 3 Solution

Assignment 3 Solution

```
#pragma omp parallel for num_threads(num_thrds) private(h,w) collapse(3)
for (i = 0; i < newImageHeight; i++) {
    for (j = 0; j < newImageWidth; j++) {
        for (d = 0; d < 3; d++) {
            for (h = i; h < i + filterHeight; h++) {
                for (w = j; w < j + filterWidth; w++) {
                    newImage[d][i][j] += filter[h-i][w-j] * image[d][h][w];
                }
            }
        }
    }
}
```

- Remember to make private data private
- collapse does not really give any speedup here
- Order of floating point operations matters!

Assignment 4

Assignment 4: `familytree`

You have 1 week time for this assignment

Family Tree Algorithm

- The given algorithm computes the IQ for all members in a family.
- It recursively traverses all generations (child $\rightarrow$ {mother, father}).
- At the end, all geniuses (IQ $\geq$ 140) are printed at the end.

- Parallelize the sequential family tree algorithm with OpenMP.
- Try to optimize it / reduce the overhead for tasking.
- The goal is a speedup of ≥ 10.

Assignment 4: `familytree_seq.c`

```c
#include "familytree.h"

int traverse(tree *node, int num_threads) {
    if (node == NULL) return 0;

    int father_iq, mother_iq;

    father_iq = traverse(node->father, num_threads);
    mother_iq = traverse(node->mother, num_threads);

    node->IQ = compute_IQ(node->data, father_iq, mother_iq);
    genius[node->id] = node->IQ;
    return node->IQ;
}
```

Assignment 4: `familytree` with OpenMP - Provided Files

- Makefile
  - contains rules to build executables
  - available targets: parallel, sequential, unit_test, all (default), clean
  - 'mode=debug make [target]' to build debug version, use 'make clean' before
- main.c
  - main function - argument handling + call familytree algorithm
- familytree.h
  - Header file for familytree.h and familytree_*.c
- familytree.c
  - Defines the familytree logic
- ds.h / ds.c
  - Header and definition for the needed datastructures
- familytree_seq.c
  - Sequential version of `traverse()`.
- student/familytree_par.c
  - Implement the parallel version in this file

Assignment 4: `familytree` with OpenMP - Provided Files (Cont.)

- vis.h / vis.c
  - The visualization component
- unit_test.c
  - The unit tests that execute both the serial and parallel version to compare results.