

Parallel programming

OpenMP part 2





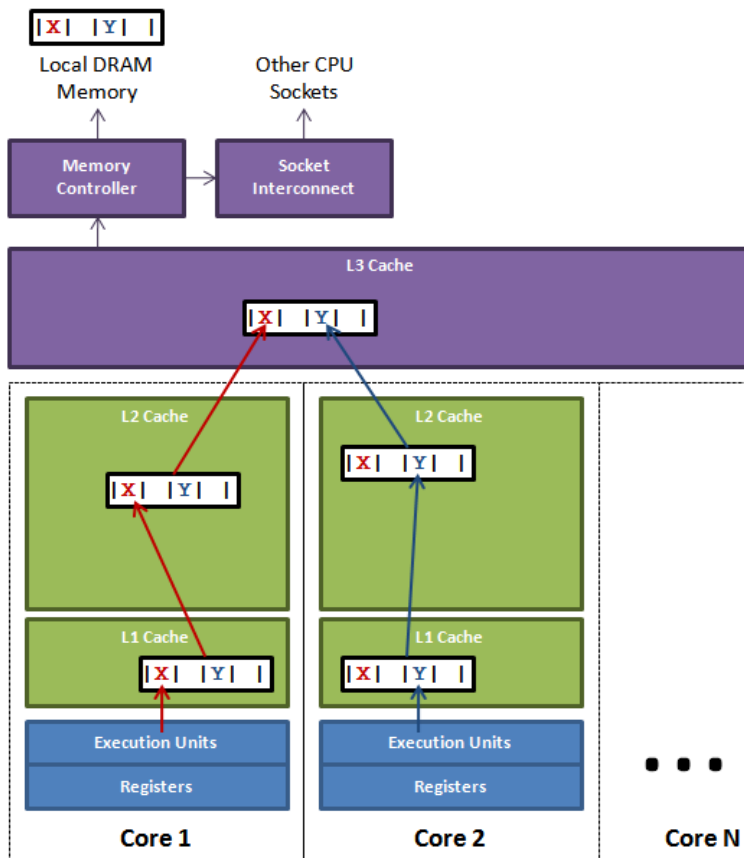
Try the example at first

Run `example FalseSharing.cpp`



What? False sharing

- Cache related problem: each of the two threads modifies own variable that resides in the same cache line → modifications from one thread are propagated to another thread by cache line invalidation



source



False sharing detection

- Can be detected using Intel VTune, only Intel processors
 - Microarchitecture Exploration → Summary → L3 Bound → Contested Accesses
 - (driver for event based sampling must be installed and on some platforms, HyperThreading has to be disabled)





Atomic

- OpenMP critical section is intended for general code to avoid data races
- Atomic operations are more efficient if the critical section can be transformed to atomic hardware instructions

```
int sum = 0;  
int currentSum;
```

```
#pragma omp atomic read  
currentSum = sum;
```

```
#pragma omp atomic write  
sum = 0;
```

```
#pragma omp atomic update  
sum += 10;
```

```
#pragma omp atomic capture  
{  
    currentSum = sum;  
    sum += 10;  
}
```

Updates the value of a variable while capturing the original or final value of the variable atomically



Example

- Write parallel vector normalization using parallel for and atomic operation
 - Implement method `normalizationParallelForAndAtomic` in `VectorNormalization.cpp`

To remind normalization:

$$\|\vec{a}\| = \sqrt{a_1^2 + a_2^2 + \cdots + a_n^2}; \vec{a} \in \mathbb{R}^n$$

$$\vec{n} = \frac{\vec{a}}{\|\vec{a}\|} = \left(\frac{a_1}{\|\vec{a}\|}; \frac{a_2}{\|\vec{a}\|}; \cdots; \frac{a_n}{\|\vec{a}\|} \right)$$



Scheduling of work

- Distribution of work among threads in parallel for
 - `#pragma omp parallel for schedule(...)`
 - policy: static, dynamic, guided
- Why? Different scenarios require different policies for efficient execution



Scheduling: static

```
#pragma omp parallel for schedule(static, chunkSize) num_threads(4)
```

- Divides the iterations into chunkSize and distributes them in circular order among threads.

```
schedule(static, 4):
```

```
*****
      *****
    *****
  *****
*****
```

```
schedule(static, 8):
```

```
*****
      *****
    *****
  *****
*****
```




Scheduling: dynamic

```
#pragma omp parallel for schedule(dynamic, chunkSize) num_threads(4)
```

- Divides the iterations into chunkSize. Threads execute the chunks as they finish.

```
schedule(dynamic, 4):
```

```
      ****                      ****                      ****
****          ****          ****          ****          ****
      ****          ****          ****          ****          ****
          ****                      ****                      ****
```

```
schedule(dynamic, 8):
```

```
      *********                      *********
          *****                      *****
          *****                      *****
*****          *****          *****          *****
          *****
```




Vectorization

- Performs the **Same Instruction on Multiple Data** - SIMD
- Special vector instructions and registers

a	2.1	1.6	3.2	0.2
	+	+	+	+
b	1.5	6.2	4.4	1.4
	=	=	=	=
z	3.6	7.8	7.6	1.6

```
#include <immintrin.h>
```

```
_m256d a;  
_m256d b;  
_m256d z = _mm256_add_pd(a, b);
```

Vectorization using intrinsic functions

- History
 - MMX (1997): 64b registers (e.g., 2x32b ints), only integers
 - SSE (1998): 128b registers, supports floats
 - SSE2 (2000): supports doubles
 - AVX (2011): 256b registers



Vectorization in OpenMP

- Use **simd** directive

```
#pragma omp simd  
for (int i = 0; i < size; i++) {  
    w[i] = u[i] * v[i];  
}
```

Loop is split into chunks that fit into SIMD register. No parallelization.

Preferably, use constants instead of function calls for iteration bounds in SIMD loops.

```
#pragma omp parallel for simd  
for (int i = 0; i < size; i++) {  
    w[i] = u[i] * v[i];  
}
```

Distribute iterations across team of threads. Iteration of one thread are then split into chunks that fit into SIMD register.



HELP! Code is not vectorized

- Sometimes, compilers need some guidance for successful vectorization
 - Number of loop iterations known before loop execution
 - No **break**
 - **if** statement only as masked assignment
 - No function calls (basic math are allowed)
 - Avoid loop dependencies (e.g., Read-After-Write is not vectorizable)
 - Unit strides are recommended (informally: iterate on the rightmost index for multidimensional arrays)
 - More information
 - <https://www.cac.cornell.edu/education/training/StampedeJan2017/Stampede2-VectorizationOnKNL.pdf>
 - https://easyperf.net/blog/2017/11/10/Tips_for_writing_vectorizable_code
- For g++
 - why vectorization did not occur? Use flag **-fopt-info-vec-missed**
 - check whether vectorization occurred

```
>> g++ -fopenmp -fopt-info-vec -O3 VectorNormalization.cpp
VectorNormalization.cpp:125:26: note: loop vectorized
VectorNormalization.cpp:131:12: note: loop vectorized
```



Example

- Try vector normalization using OpenMP SIMD
 - Implement method `normalizationParallelSimd` in `VectorNormalization.cpp`

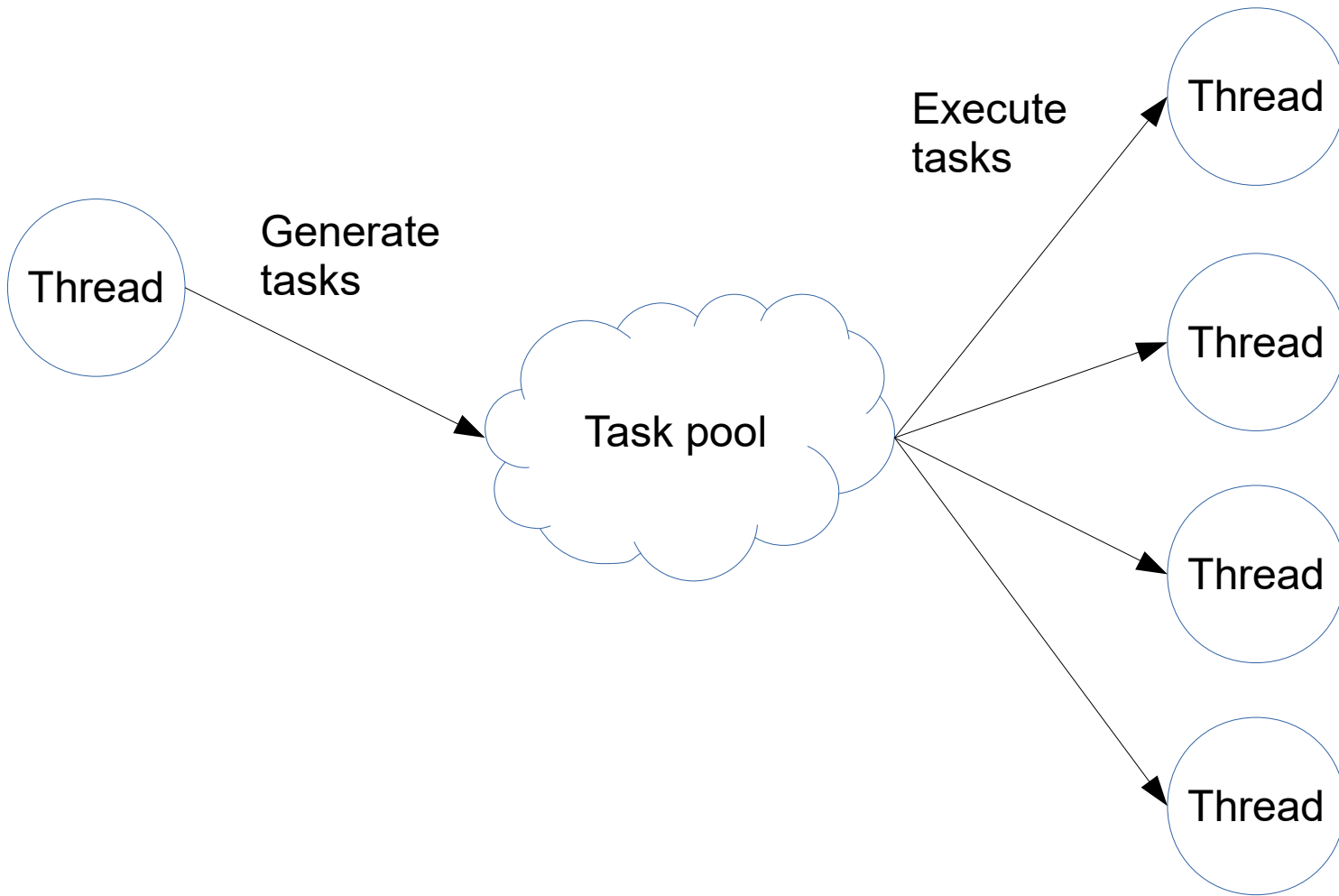


Tasks

- A task is block of code to be run in parallel
- When a thread encounters a task construct, it may either run it immediately or defer its execution
- Deferred tasks are added to a task pool, which is processed by all threads in the team



Task pool





Task pool

```
#pragma omp parallel
{
    #pragma omp single
    {
        for (int i = 0; i < 10; i++) {
            #pragma omp task
            {
                cout << "Iteration " << i
                    << " processed by thread " << omp_get_thread_num() << endl;
            }
        }
    }
}
```

One thread generates tasks

Generation of task

Output:

```
Iteration 0 processed by thread 1
Iteration 2 processed by thread 3
Iteration 3 processed by thread 1
Iteration 1 processed by thread 0
Iteration 5 processed by thread 1
Iteration 4 processed by thread 3
Iteration 7 processed by thread 1
Iteration 8 processed by thread 3
Iteration 9 processed by thread 1
Iteration 6 processed by thread 0
```

Iterations processed by all
threads in team



Tasks vs Sections

- Sections are for static number of parallel regions
 - Previous example cannot be reimplemented with sections, code will not compile
- error: work-sharing region may not be closely nested inside of work-sharing



Tasks synchronization

```
#pragma omp parallel
{
    #pragma omp single
    {
        #pragma omp task
        cout << "I'm a lonely task outside of task group :(" << endl;

        #pragma omp task
        cout << "I'm a lonely task outside of task group :(" << endl;

        #pragma omp taskwait ←
        #pragma omp taskgroup
        {
            #pragma omp task
            cout << "I'm a happy task inside of task group :)" << endl;

            #pragma omp task
            cout << "I'm a happy task inside of task group :)" << endl;
        }
    }
}
```

Waits on all tasks generated by the current task from the beginning

Waits until the completion of all enclosed and descendant tasks

Output:

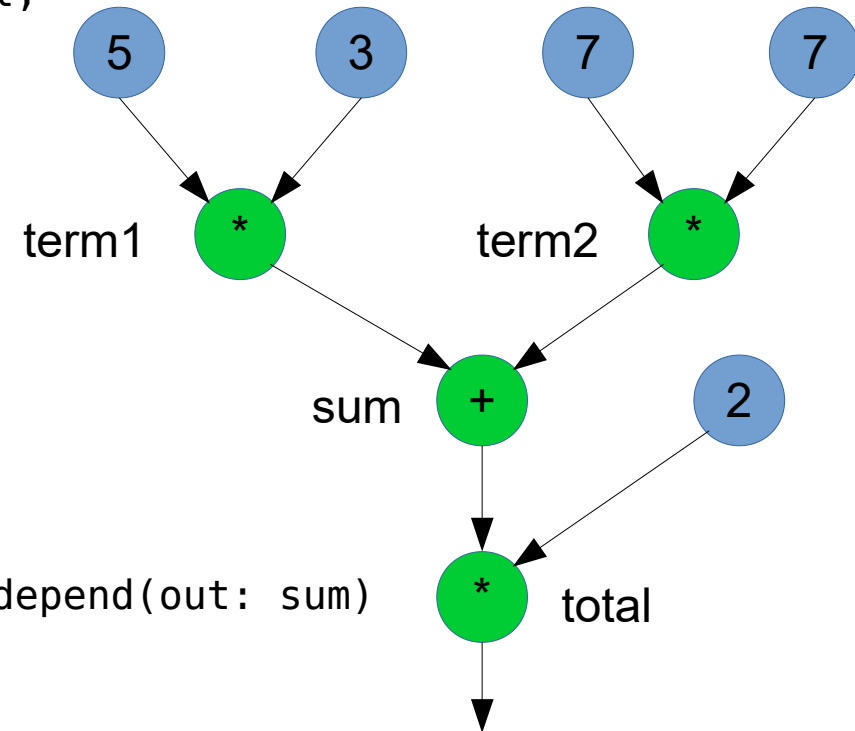
```
I'm a lonely task outside of task group :(
I'm a lonely task outside of task group :(
I'm a happy task inside of task group :)
I'm a happy task inside of task group :)
```



Tasks with dependencies

```
cout<< "Evaluating expression: 2*(5*3+7*7)" << endl;  
int term1 = 0, term2 = 0, sum = 0, total = 0;
```

```
#pragma omp parallel  
{  
    #pragma omp single  
    {  
        #pragma omp task depend(out: term1)  
        term1 = 5*3;  
  
        #pragma omp task depend(out: term2)  
        term2 = 7*7;  
  
        #pragma omp task depend(in: term1, term2) depend(out: sum)  
        sum = term1+term2;  
  
        #pragma omp task depend(in: sum)  
        total = 2*sum;  
  
        #pragma omp taskwait  
        cout << "Final value of the expression: " << total << endl;  
    }  
}
```



Output:

```
Evaluating expression: 2*(5*3+7*7)  
Final value of the expression: 128
```

Without taskwait the total could be 0!



Data scoping for tasks

- Similar as for sections, with one notable exception:
 - Variables of orphaned tasks (not directly in parallel section) **are firstprivate by default!**

```
void task(vector<double> &u) {  
    #pragma omp task  
    cout << "In orphaned task: " << &u << endl;  
}
```

...

```
cout << "In main thread: " << &u << endl;  
#pragma omp parallel num_threads(1)  
{  
    #pragma omp task  
    cout << "In explicit task: " << &u << endl;  
}
```

```
#pragma omp parallel num_threads(1)  
{  
    #pragma omp single  
    task(u);  
}
```

Can be corrected by using shared(u)

Output:

```
In main thread: 0x7fff3fd79650  
In explicit task: 0x7fff3fd79650  
In orphaned task: 0xc14b50
```



Example

- Implement parallel merge sort using tasks
 - Use the provided skeleton MergeSort.cpp

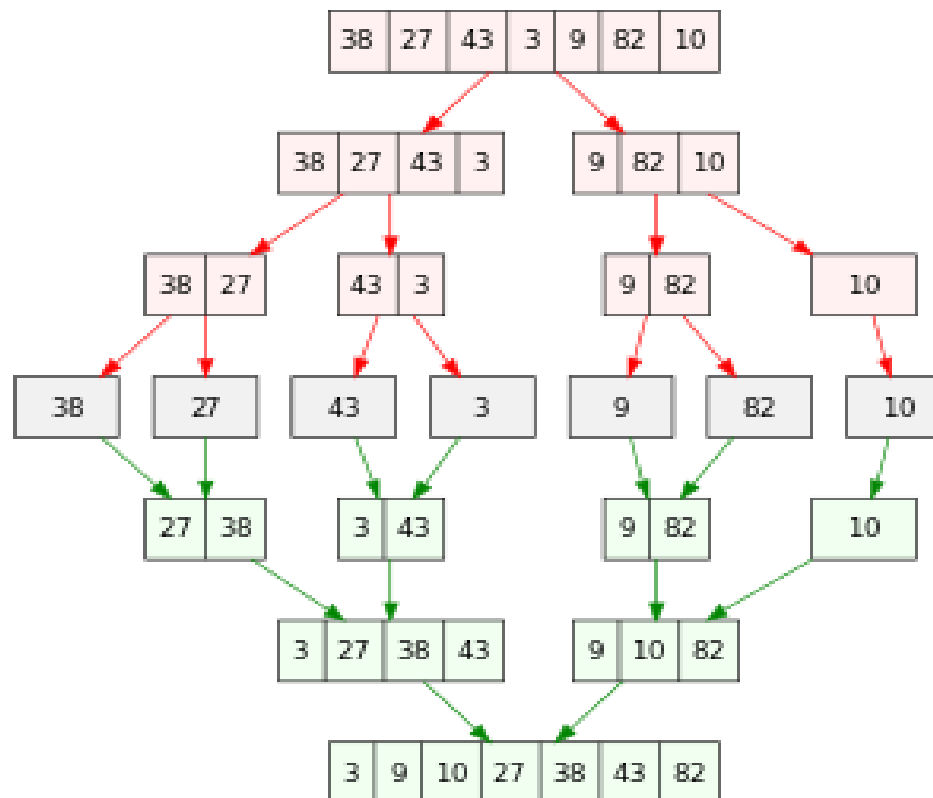


image source



References

- <http://jakascorner.com/blog/2016/06/omp-for-scheduling.html>
- https://en.wikipedia.org/wiki/Merge_sort