Threaded Programming coursework I: benchmarking OpenMP schedules

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Abstract

Keywords:

1. Introduction

This paper documents the results of a benchmark performed on a scientific program. The program is written in the Fortran programming language and performs element-wise computations on matrices and vectors (using nested do-loops, not Fortran's array operations). It contains two of these matrix/vector operations—in this paper called critical sections.

Both critical sections are suitable for speeding up with OpenMP's loop construct, distributing the computation on multiple threads of execution. The loop construct provides the `schedule` clause, which determines the division of the loop-iterations among the OpenMP threads (see OpenMP Architecture Review Board, 2015, Chapter 2.7.1).

The benchmark consists of two phases. The goal of the first phase is to compare different scheduling options of the OpenMP library and how they effect the execution speed (measured in seconds) of the two critical sections of the program. The second phase provides data on how well the fastest scheduling options for both critical sections scale with different amounts of threads.

OpenMP version 4.5 was used and the benchmark was performed on the backend of the Cirrus supercomputer (see OpenMP Architecture Review Board, 2015; EPCC, 2019). The program was compiled with the Intel Fortran Compiler (`ifort`) version 17.0.2, with the maximum optimization provided (optimization level `O3`) (see Intel, 2016).

First, this paper describes the conducted benchmark, before presenting the results. At last the results are discussed and a conclusion is drawn.

2. Experiment

This chapter will describe the performed benchmark. First the two critical sections are described mathematically, followed by a description of the benchmark.

Let $n \in \mathbb{N}$ be a positive integer. Let $A : n \times n$ and $B : n \times n$ be two matrices, $A, B \in \mathbb{R}^n \times \mathbb{R}^n$. Let $A(i,j); 1 \leq i,j \leq n$ be the element of A in the ith row and the jth column. Every element in A is initialized to 0 and every element in B is set according to: $B(i,j) = \pi(i+j); i,j = 1,\dots,n$.

The first critical section updates A:

$$A(i,j) = A(i,j) + \cos(B(i,j)); i,j = 1,\dots,n. \tag{1}$$

Both critical sections are executed multiple times, which is the reason $A(i,j)$ on the right-hand side of (1) can not be substituted to 0.

For the second critical section, let $\vec{c}$ be the zero vector of size n. Let $\vec{j}_{\max} \in \mathbb{N}^n$ be another n-sized vector. $\vec{j}_{\max}$ is set to:

$$i = 1,\dots,n : \vec{j}_{\max}(i) = \begin{cases} n & \text{if } i \bmod 3\lfloor \frac{i}{30} \rfloor + 1 = 0 \\ 1 & \text{if } i \bmod 3\lfloor \frac{i}{30} \rfloor + 1 \neq 0 \end{cases}. \tag{2}$$

The matrix B' is set to $B'(i,j) = (ij+1)n^{-2}; i,j = 1,\dots,n$.

The second critical section updates $\vec{c}$:

$$\vec{c}(i) = \sum_{j=1}^{\vec{j}_{\max}(i)} \sum_{k=1}^{j} \vec{c}(i) + k \ln(B'(j,i))n^{-2}, i = 1,\dots,n. \tag{3}$$

Since both (1) and (3) are element-wise independent, the computation of every element can be distributed over multiple processes.

It should be noted here, that (1) is a perfect computational cube of $n \times n$. That means, that every iteration—each a manipulation of a single cell $A(i,j)$—contains the same amount of instructions, making it trivial to split the iterations and having a balanced distribution of work per thread.

On the other hand one can see that (3) does not behave in the same way. Each iteration is dependent on $\vec{j}_{\max}(i)$, which is not constant. Instead, $\vec{j}_{\max}(i)$ equals either 1 or n and the distribution of $\vec{j}_{\max}(i) = n$ is asymmetric, since the modulus in (2) changes depending on the iteration i. The consequence is, that for small i, $\vec{j}_{\max}(i) = n$ more often, which means that the first iterations are computationally more heavy and time consuming than the later iterations.

The benchmark consists of two phases. In the first phase, different scheduling options are compared using four threads and the fastest scheduling option for each critical section is determined. The second part of the benchmark tests how well the fastest scheduling options scale with different amounts of threads. For the benchmark n was set to 729.

The different scheduling options used in the first phase are:

- Auto
- Static
- Static, Dynamic, Guided, all with different chunk sizes of: 1, 2, 4, 8, 16, 32, 64

The fastest scheduling options for the critical sections are then run with 1, 2, 4, 6, 8, 12 and 16 threads during the second phase of the benchmark.

Like stated in the introduction, both benchmark phases are executed on the Cirrus backend with exclusive access to one node. Every scheduling option in phase one and every amount of threads in phase two were executed 100 times and the average and median walltime—in seconds—were measured with the timing routine `omp_get_wtime`, provided by OpenMP (see OpenMP Architecture Review Board, 2015, Chapter 3.4.1). The average walltime was used as the decisive criteria for execution speed.

3. Results

Table 1 lists the average and median walltime in seconds for the execution of the critical sections, determined in phase one of the benchmark.

4. Discussion

5. Conclusion

References

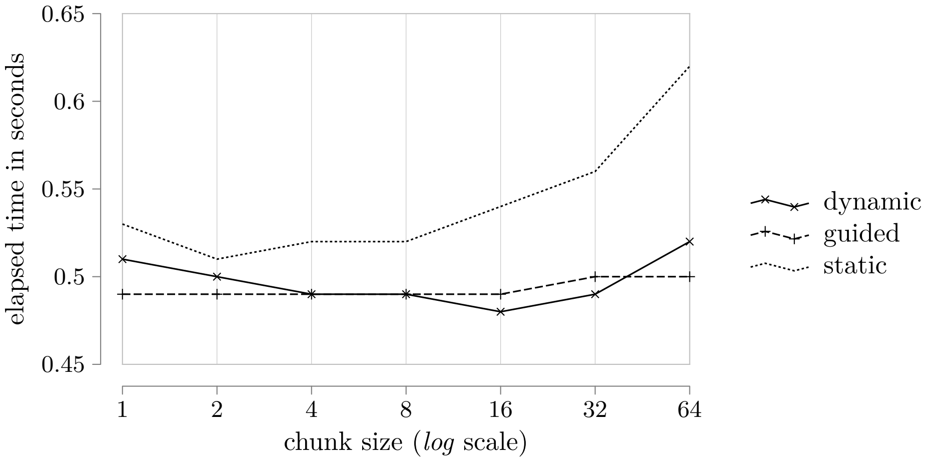
EPCC. Cirrus, 2019. URL `https://www.cirrus.ac.uk`.

Intel. Intel Fortran Compiler 17.0 for Linux, 2016. URL `https://software.intel.com/en-us/articles/intel-fortran-compiler-170-for-linux-release-notes-for-intel-parallel-studio-xe-2017`.

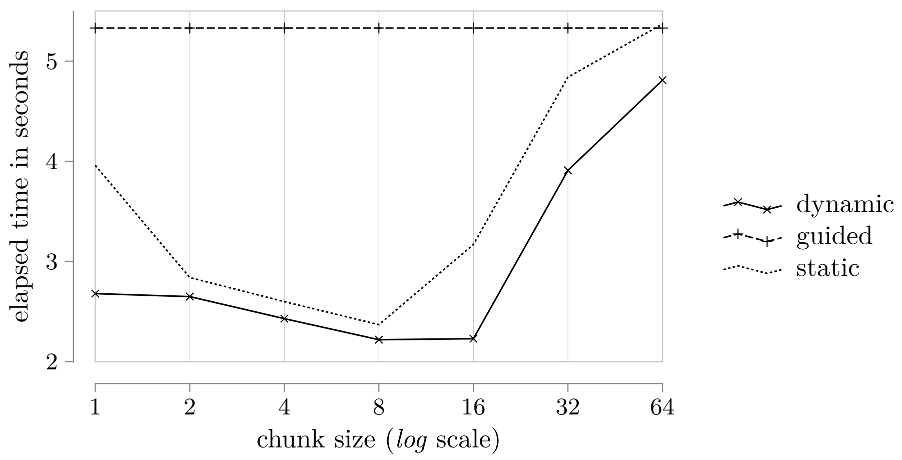
OpenMP Architecture Review Board. OpenMP application program interface version 4.5, 2015. URL `https://www.openmp.org/wp-content/uploads/openmp-4.5.pdf`.

schedule	critical section 1		critical section 2	
	mean	median	mean	median
Sequential	1.62	1.61	8.57	8.56
Auto	0.49	0.48	5.32	5.32
Static	0.83	0.84	6.18	6.19
Dynamic, 1	0.51	0.51	2.68	2.57
Dynamic, 2	0.50	0.49	2.65	2.57
Dynamic, 4	0.49	0.49	2.43	2.39
Dynamic, 8	0.49	0.48	**2.22**	**2.22**
Dynamic, 16	**0.48**	**0.48**	2.23	2.23
Dynamic, 32	0.49	0.48	3.91	3.91
Dynamic, 64	0.52	0.51	4.81	4.81
Guided, 1	0.49	0.49	5.33	5.34
Guided, 2	0.49	0.48	5.33	5.33
Guided, 4	0.49	0.49	5.33	5.33
Guided, 8	0.49	0.48	5.33	5.33
Guided, 16	0.49	0.48	5.33	5.33
Guided, 32	0.50	0.49	5.33	5.33
Guided, 64	0.50	0.49	5.33	5.33
Static, 1	0.53	0.53	3.96	3.93
Static, 2	0.51	0.51	2.84	2.81
Static, 4	0.52	0.52	2.60	2.57
Static, 8	0.52	0.52	2.37	2.37
Static, 16	0.54	0.53	3.17	3.18
Static, 32	0.56	0.56	4.84	4.84
Static, 64	0.62	0.63	5.37	5.38

Table 1: Results of phase one of the benchmark. Displayed are average and median walltime in seconds for every scheduling option for both critical sections. The fastest scheduling options are marked with bold font-weight.

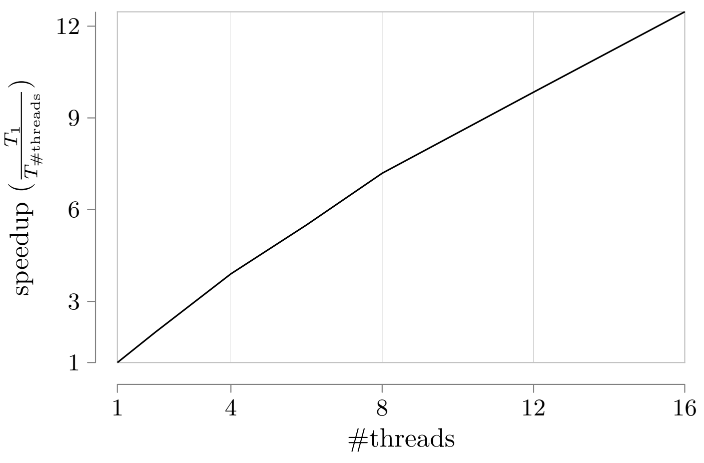


(a) Critical section 1.

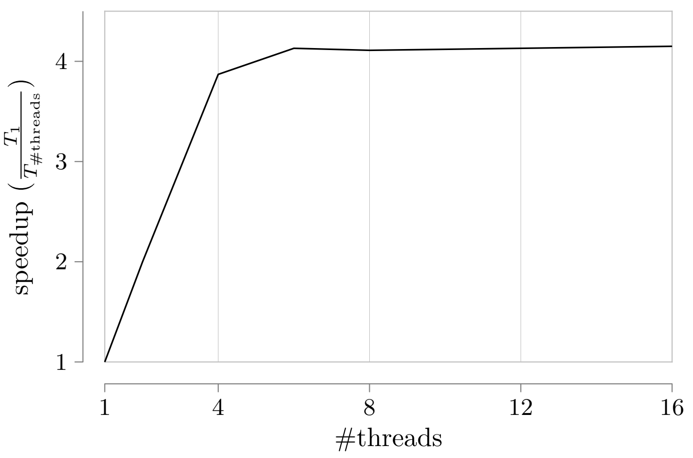


(b) Critical section 2.

Figure 1: Plots on how the chunk size clause changes the execution speed of the dynamic, guided and static scheduling options, for both critical sections.



(a) Critical section 1.



(b) Critical section 2.

Figure 2: Plots on how the execution speed varies with the amount of threads. The plots show how much faster more threads are, compared to just one thread.

#threads	critical section 1		critical section 2	
	mean	median	mean	median
1	1.87	1.87	8.59	8.59
2	0.94	0.93	4.30	4.30
4	0.48	0.48	2.22	2.22
6	0.34	0.34	2.08	2.08
8	0.26	0.26	2.09	2.10
12	0.19	0.18	2.08	2.08
16	0.15	0.14	2.07	2.07

Table 2: Results of phase two of the benchmark. Displayed are average and median walltime in seconds for the fastest scheduling options from phase one, for each critical section, executed with different amounts of threads.