Threaded Programming coursework I: benchmarking OpenMP schedules

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Abstract

The benchmark of a scientific program presented in this paper compares different OpenMP schedules based on how well they increase the execution speed.

The scientific program contains two critical sections which are suitable for speeding up with the OpenMP parallel do-loop directive. Both were tested with different schedules on four threads and the fastest schedule for each section was determined. In the second phase of the benchmark it was tested how well the fastest schedules scale with less and more than four threads.

The benchmark was executed on the Cirrus supercomputer with exclusive access to one back end node. The results of this benchmark show, that, based on the schedule alone the speed can increase by a factor of 2.7. This paper discusses the results of the benchmark and furthermore raises questions concerning performance anomalies and further optimizations. Further ideas for a follow-up benchmark testing changes which could result in higher performance are given.

Keywords: OpenMP, parallel computing

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 schedules 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 schedules for both critical sections scale with different amounts of threads.

OpenMP version 4.5 was used and the benchmark was performed on the back end 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

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: $B(i,j) = \pi(i+j); i,j = 1,\ldots,n$.

The first critical section updates A:

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

This equation in matrix form would be: $A = A + \cos(B)$.

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:

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

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

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

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

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) looks computationally symmetric. That means, that every iteration—each a manipulation of a single cell $A(i,j)$—is the same operation, 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. For example, $\vec{j}_{\max}(i) = n$ for every element in the interval $i \in (1, 29)$, while $\vec{j}_{\max}(i) = n$ is true for only 7 elements in $i \in (30, 59)$ and the amount keeps decreasing with bigger i. This has the consequence, that the first iterations are computationally more heavy and time consuming than the later iterations.

For both phases of the benchmark, n was set to 729. The different schedules 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 schedules 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 back end with exclusive access to one node. Every schedule from 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. The median was used as the secondary, tie-breaking criteria.

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.

Sequential is not a schedule. It represents execution time of the critical section in a sequential, not parallelized manner.

One can see, that for the first—the symmetric—critical section the schedules do not differentiate much concerning the execution time. Especially the Auto, Dynamic, n and Guided, n schedules produce results between 0.48 and 0.52 seconds of average execution time. Static, n performs slightly worse, all producing an average execution time between 0.51 and 0.56 seconds, except Static, 64, which performs worse with an average execution time of 0.62 seconds. The Static schedule, which just splits the iterations in #threads (in this case four) approximately equal chunks, performs the worst with an average execution time of 0.83 seconds (see Mark Bull, 2019).

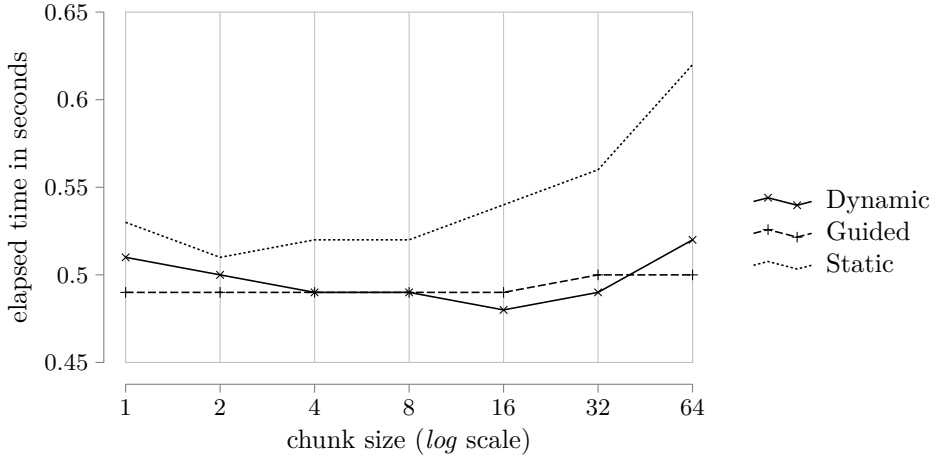
The best schedule for the first critical section is Dynamic, 16, with an average and median execution time of 0.48 seconds.

The schedules differ much more in execution time for the second critical section, compared to the first one.

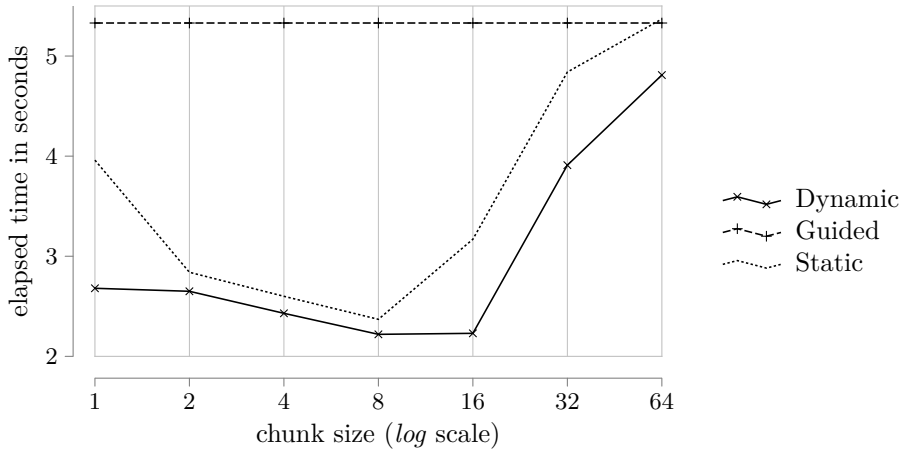
The difference between Dynamic, 8 (fastest) and Static (slowest) is nearly 4 seconds, which makes Static approximately 2.8 times slower than Dynamic, 8. For comparison, the slowest schedule for the first critical section is just approximately 1.7 times slower than the fastest schedule.

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 schedule for both critical sections. The fastest schedules are marked with a 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 schedules, for both critical sections.

#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 schedules from phase one, for each critical section, executed with different amounts of threads.

Guided, n and Auto, which were close to fastest for the first critical section, perform worse on the section critical section. All are approximately 2.4 times slower than Dynamic, 8.

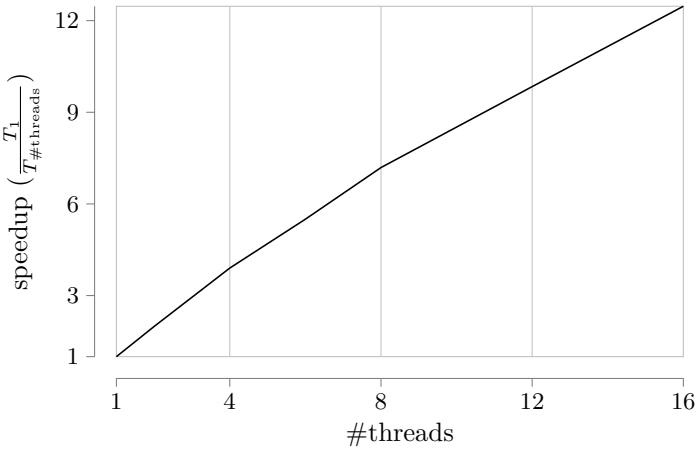
Static, n fluctuates the most with different chunk sizes n. Static, 8, with 2.37 seconds average execution time, is the third fastest schedule, while Static, 64 is the second slowest schedule with 5.37 seconds average execution time.

The fluctuation of the average execution time, based on different chunk sizes can be seen in Figure 1.

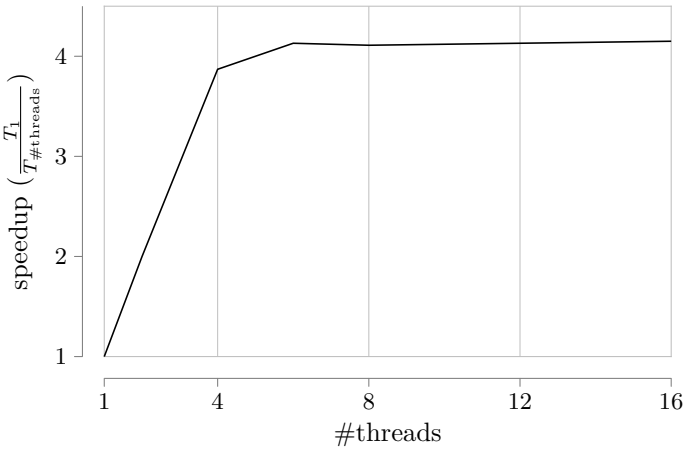
During the second phase of the benchmark the two scheduling options resulting in the fastest average execution time were tested with different amounts of threads. The fastest schedule for the first critical section was Dynamic, 16. For the second critical section Dynamic, 8 resulted in the fastest average execution time.

Table 2 lists the average and median execution time in seconds for both schedules when run with 1, 2, 4, 6, 8, 12 and 16 threads.

Figure 2 displays how much using more threads gains in exectution speed, compared to using just one thread (sequential execution). While for the first critical section the speedup of using more threads grows linear, the execution time for the second critical section stops being faster after 6 threads (see Table 2, Figure 2).



(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.

4. Discussion

There are several statements to make about why some schedules outperform each other. It should be noted that this chapter discusses some ideas on why the performance of different schedules differ. Follow-up benchmarks would be needed to confirm or refute them.

During the first critical section only Static and Static, n perform worse than the others. Guided, n has approximately the same performance as Dynamic, n (it is even more constant over the different chunk sizes). This suggests, that the reason why Static and Static, n perform worse must lie in the later iterations. This could have two reasons: (i) longer indexing of $B(i, j)$; (ii) $\cos(x)$ takes longer to compute for bigger x (see Equation 1). Problem (ii) could easily be solved by setting $B(i, j) = B(i, j) \mod 2\pi$, since if $x \equiv y (\mod 2\pi)$, then $\cos(x) = \cos(y)$ (follows from the fact that $\cos(x)$ has 2π as its period) (see e.g. Romanowski, 2014).

The second critical section behaves the opposite, having the more time consuming iterations at the beginning of the loop. This is validated by the bad performance of the Dynamic, n schedules, which take bigger chunks at the beginning, making them smaller the more iterations are already done. This is why all produce the same average execution time. The first iterations are the bottleneck of the second critical section.

The high imbalance is also the reason the Static, Dynamic and Guided schedules with higher chunk sizes are outperformed by smaller ones, since the better the first iterations are distributed among multiple threads, the faster the imbalance—the bottleneck—gets executed.

On the other hand, Static, 1 and Dynamic, 1 are again worse than bigger chunk sizes (2, 4, 8). This could be the result of the higher amounts of context switching and higher costs for scheduling the execution.

The imbalance is also the reason for the lack of speedup with more threads for the Dynamic, 8 schedule, determined as fastest for the second critical section during phase one (see Table 2, Figure 2). The Dynamic schedule with a smaller chunk size would probably scale better with more threads.

5. Conclusion

The benchmark shows, using an optimized schedule for a certain problem can increase the performance drastically.

The fastest schedule for the first critical section is approximately 1.7 times faster than the slowest. The second critical section—more imbalanced than the first—produces even more severe performance differences, the fastest schedule being approximately 2.8 times faster than the slowest.

On the other hand, a couple of questions about further performance increasing changes are raised.

The results for the first critical section suggests, that later iterations are more computationally expensive than the first, even though the first critical section looks like the perfect computational cube. Two reasons possible reasons are mentioned, (i) higher cost of indexing a multidimensional array with bigger indices and (ii) $\cos(x)$ takes more time for bigger x.

The other question is, if for the second critical section schedules with smaller chunk sizes scale better (because they better divide the bottleneck created by the computational imbalance over the iterations) with more threads than the best schedule determined on four, like done in this benchmark.

To answer those two raised questions, a follow-up benchmark is necessary.

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