

# Arquitectura de ordenadores. Practice 4.

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## 1 Exercise 1: Basic OpenMP programs

### 1.1 *Is it possible run more threads than cores on the system? Does it make sense to do it?*

It is possible to do so: if we first execute `omp1` without arguments to see the available cores and then we execute it again with a number of threads higher than the amount of cores, we will see that the execution is carried out without problems. Using more threads than cores may make no sense when the goal is simply to parallelize a single task because the threads will interrupt each other. However, if there are several tasks to be run at the same time and any of them may provoke the thread to go asleep, then using more threads could help to take advantage of the time that particular thread is asleep.

### 1.2 *How many threads should you use on the computers in the lab? And in the cluster? And on your own team?*

For a general situation, the number of threads to be used is the one determined by the function `omp_get_max_threads()`. Indeed this value used by default.

### 1.3 *Modify the `omp1.c` program to use the three ways to choose the number of threads and try to guess the priority among them*

The priority order is: `OMP_NUM_THREADS < omp_set_num_threads() < #pragma omp parallel num_threads(numthr)`

### 1.4 *How does OpenMP behave when we declare a private variable?*

Each thread created will create its own (new) variable.

### 1.5 *What happens to the value of a private variable when the parallel region starts executing?*

The variable is not necessarily initialized when allocated in each thread stack, although when executing `omp2` in the lab computers, it is initialized as if it were a *firstprivate* variable (with the value of the variable previous to the parallel section). Furthermore, it is private to each thread so its value will only change because of instructions performed by that specific thread.

### 1.6 *What happens to the value of a private variable at the end of the parallel region?*

After the parallel region, the master threads resumes execution and the value of the variable is the one from before the parallel execution. Private variable are local to the threads and the parallel region, so they are deleted when the threads terminate.

### 1.7 *Does the same happen with public variables?*

Public variables are shared by all threads (no copies of the variable are created for each thread); therefore, after the parallel region, the value will be determined by the code executed in the parallel region (and, perhaps, by the order of execution of the several threads).

## 2 Exercise 2: Parallelize the dot product

### 2.1 *Run the serial version and understand what the result should be for different vector sizes.*

As we are calculating the dot product of two vectors of size  $M$  where all the components are 1, the expected output is  $M$ .

### 2.2 *Run the parallelized code with the `openmp` pragma and answer the following questions in the document*

The parallel version is not working due to the fact that variable `sum` is being shared (default mode). So we have several threads writing in the same variable at the same time which produces a data race.

### 2.3 *Modify the code and name the program `pescalar_par2`. This version should give the correct result using the appropriate pragma:*

The modification needed is adding the pragma clause just before the calculation. Both *pragmas* solve the data race. Nonetheless, the way they achieved so is different. *Critical* pragma implies the use of a mutex

so only one thread can access the block at a time (which is quite expensive in execution time) whereas *atomic* ensures that the whole calculation (line 42) is executed as a single operation. The result is exactly the same as we are enclosing just a sentence of code, however, the second option is considerably faster.

```
...
#pragma omp parallel for
for(k=0;k<M;k++)
{
    #pragma omp atomic
    sum = sum + A[k]*B[k];
}
...
```

2.4 Modify the code and name the resulting program *pescalar\_par3*. This version should give the correct result using the appropriate pragma:

If we use *reduction* we get better results than the ones obtained with *atomic*. This is the appropriate solution in this case, because it is the optimized version meant for this specific task.

2.5 Run time analysis

We have written a script to test this (*scr2.threshold.sh*). As can be seen in the following figure (fig. 1), the parallel version (in the lab computers, that use 4 threads) is very inconsistent. However, the first value that meets the requirements is  $T = 1200000$ :

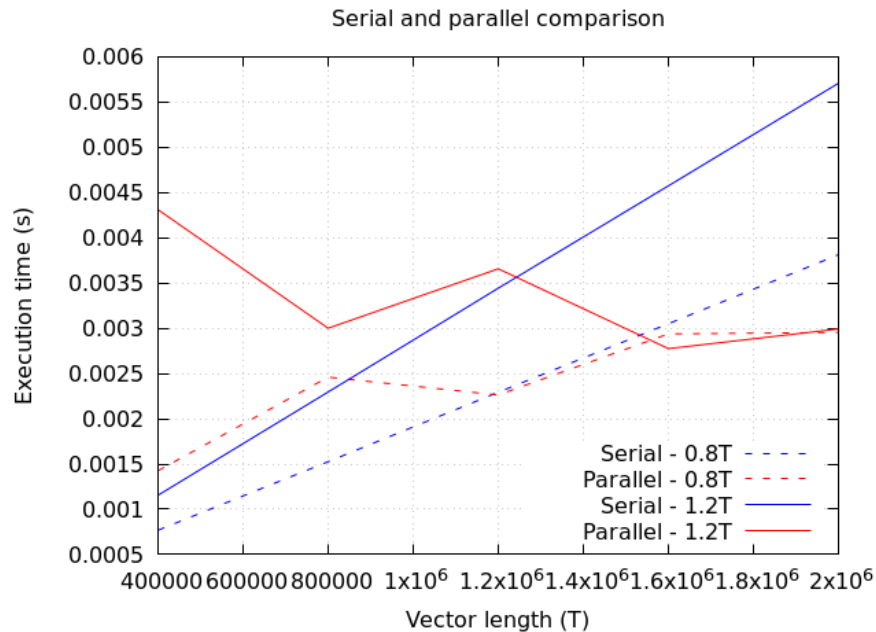


Figure 1: Search for threshold in the lab computers

## 2.6 (Optional) Exhaustive analysis

Executing the same tests in the cluster, using also 4 cores, we have reached the value that meets the requirements at, approximately,  $T = 81000$ , as can be seen in the following figure (2):

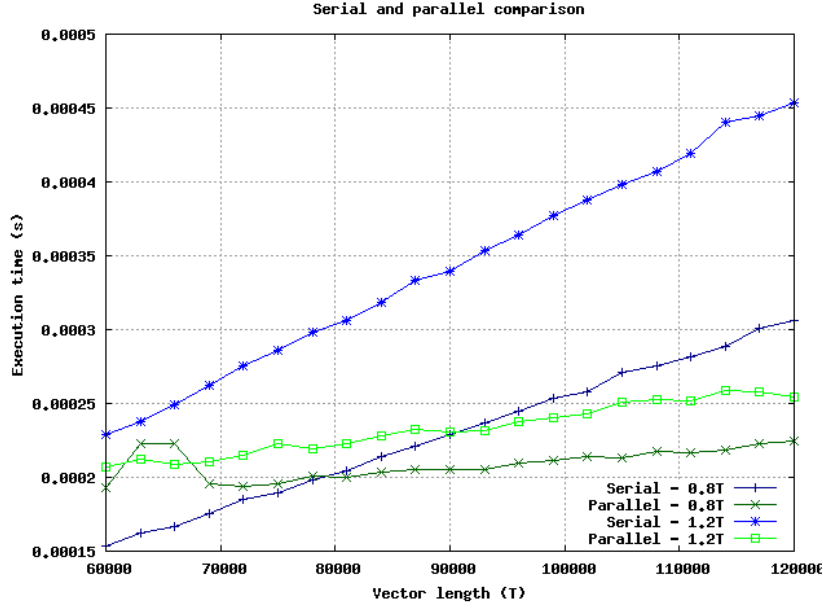


Figure 2: Search for threshold in the cluster: 4 cores

Changing the number of threads to 8, the number increases slightly, the threshold would be around  $T = 90000$ . This makes sense, because, although using 8 threads would yield a much better performance for very large matrix sizes, the threshold for which creating a higher number of threads is worth the time spent creating them is also a bit higher.

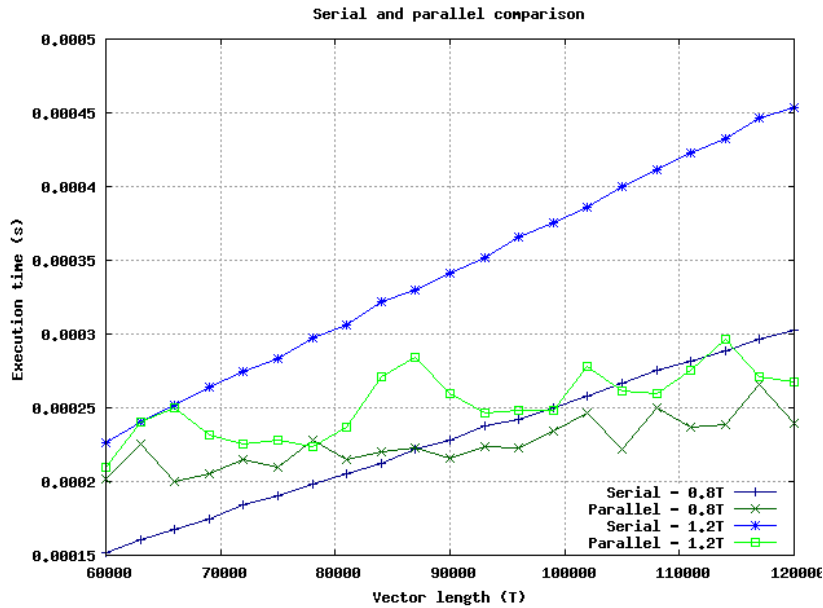


Figure 3: Search for threshold in the cluster: 8 cores

### 3 Exercise 3: Parallel matrix multiplication

We have sampled times for the different programs using matrices of size 2000, which yield high enough times to make a difference between the different implementations. Here are the results:

threads	1	2	3	4
serial	53.7103	54.5405	55.4747	56.9697
loop1	56.1735	29.408	27.5136	28.2914
loop2	54.843	27.9134	18.6343	14.2978
loop3	53.3989	27.7954	18.5844	14.0748

Figure 4: Times (seconds) for the requested tests

threads	1	2	3	4
serial	1	1.01546	1.03285	1.06068
loop1	1.04586	0.54753	0.512259	0.526741
loop2	1.02109	0.519703	0.34694	0.266203
loop3	0.994202	0.517506	0.346011	0.262049

Figure 5: Ratios for the requested tests

3.1 *Which of the three versions performs the worst? Why? Which of the three versions performs better? Why?*

The worst performing version is the one that parallelizes the innermost loop, because it is forced to “fork” itself  $N^2$  times, which causes the execution to be a lot slower. The best performing one, as could be expected, is the one that parallelizes the outermost loop, it has to separate into different threads only once (the *multiplication\_loop2.c* one “forks”  $N$  times).

3.2 *Based on the results, do you think fine-grained (innermost loop) or coarse-grained (outermost loop) parallelization is preferable in other algorithms?*

Based on these results, coarse-grained parallelization is generally preferable, as it avoids slowing the execution by killing and creating threads multiple times.

Taking the best parallel version (parallelizing the outermost loop) alongside the serial version, we have tested for  $N$  between  $512 + P$  and  $512 + 1024 + P$  with increments of 64. And with the parallel version, we have tested for 2, 4 and 6 threads. These are the results:

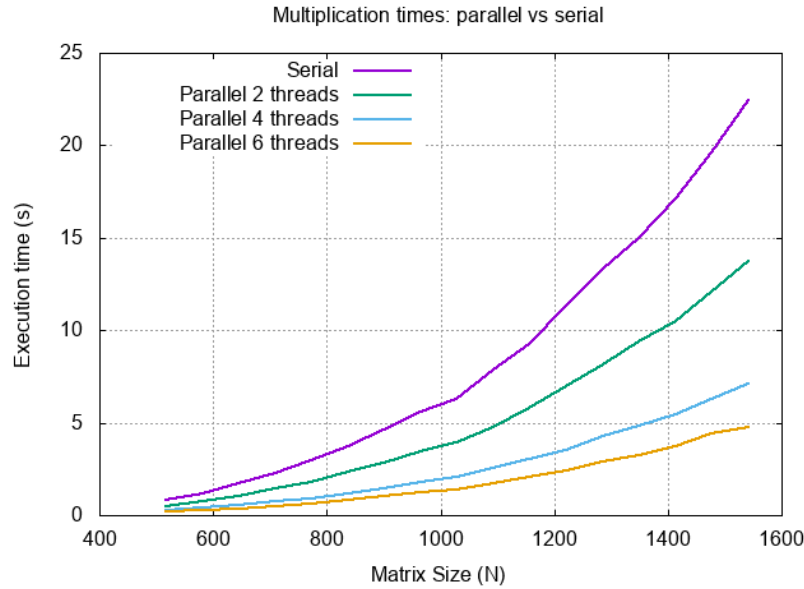


Figure 6: Time in seconds.

As expected, the plots have a cubic behaviour. Comparing the different plots, as the values of  $N$  are sufficiently large to take advantage of the parallelization, the higher the number of threads, the less time it takes to compute the multiplication. The serial version is the slowest for all of these values of  $N$ .

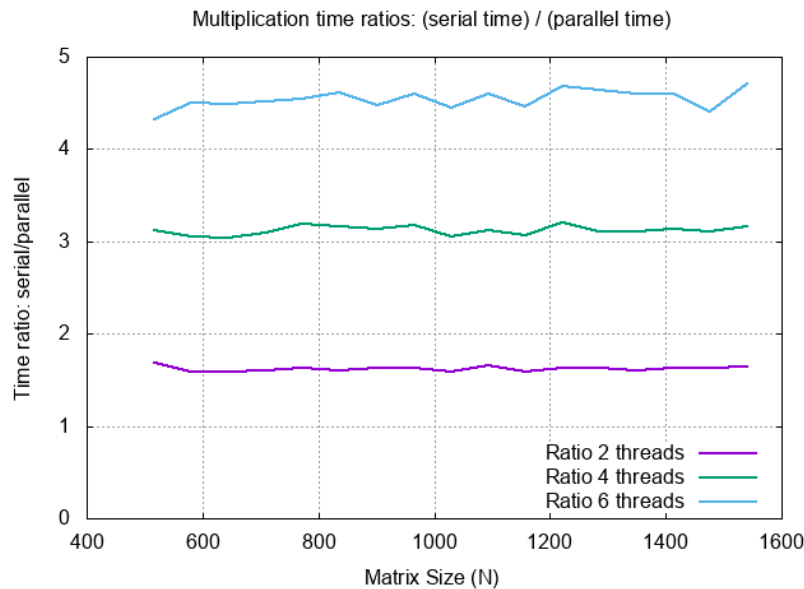


Figure 7: Time ratios.

As commented before, for the sizes that we have tested, the asymptotic behaviour is already present (as  $N$  is big enough). The four time functions have a complexity of  $\mathcal{O}(N^3)$ , which means that if we calculate the speedup for each parallel version (with different number of threads), it will stabilize around a constant in each case. This constant behaviour of the ratios is what can be seen in this plot. Again, as lower number of threads is worse than higher number of threads for big enough values of  $N$ , the constant in question is higher when the number of threads is higher.

- 3.3 If in the previous chart you did not obtain a behavior of the acceleration as a function of  $N$  that stabilizes or decreases with increasing the size of the matrix, continue increasing the value of  $N$  until you get a chart with this behavior and indicate for which value of  $N$  you begin to see the change in trend.

The values that we got already stabilize the speedup; as can be seen in figure 7, the values stabilize: for 2 threads, around 2.6; for 4 threads, around 3.1; and 6 threads, 4.6.

In order to check the values of  $N$  that stabilize the speedup, we have to check lower values:

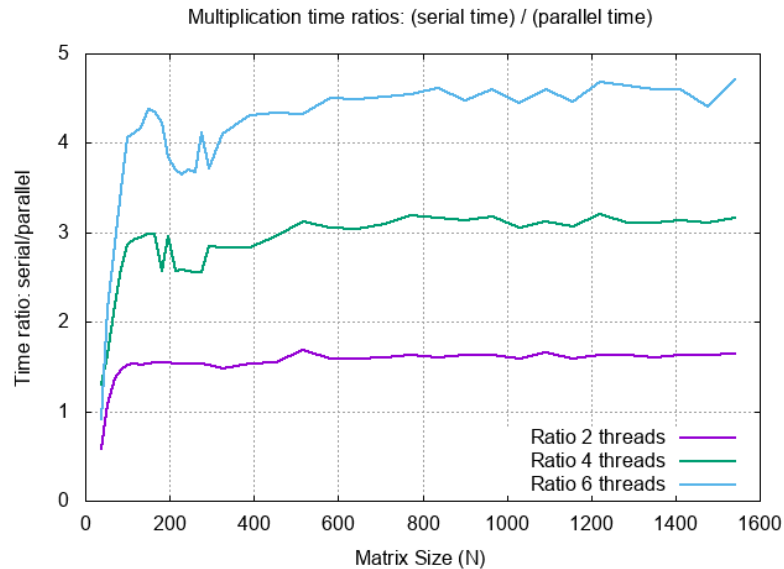


Figure 8: Time ratios extending the plot with lower values.

As we can see, with increasing number of threads, the stabilizing value increases slightly. For 2 threads, the value is around  $N = 100$ ; for 4 threads, between  $N = 130$  and  $N = 400$ , and for 6 threads, between  $N = 160$  and  $N = 450$ .

## 4 Exercise 4: Example of numerical integration

- 4.1 How many rectangles are used in the program? Which value does  $h$  take?

The number of rectangles is determined by the variable  $n$ , whose value is  $10^8$ . The variable  $h$  takes the length of the segments in which the interval  $[0, 1]$  is divided (the base of the rectangles), so it is  $h = 1/n$ . In this case,  $h = 10^{-8}$ .

- 4.2 Analyze performance

- 4.3 Regarding `pi_par2`, does it make sense to declare `sum` as private variable? What does it happen when you declare a pointer as private

In `pi_par2`, the variable `sum` (a pointer) is marked with the clause `firstprivate`. As a result, each thread creates a copy of the pointer and the value it is initialized with the one before the parallel region. So even though each thread has its own pointer, all of them point to the same memory position. Indeed, if the clause `private` is used instead of `firstprivate`, we would possibly get segmentation fault as the pointer in each thread would point to an “unknown” position outside the process memory region.

- 4.4 What are the differences between `pi_par5`, `pi_par3` and `pi_par1`? Explain the concept of false sharing. Why does `pi_par3` obtain the linesize of the cache?

False sharing occurs when the same block of memory is in the caches of different threads and it is being modified by more than one of them. Every time one thread modifies part of the block, the block becomes no valid for the rest of the threads, and therefore they need to replace the block in the cache.

Version `pi_par1` (and `pi_par2`) is a clear example of false sharing: the  $k$ -th thread modifies the position  $k$  of the array `sum` provoking that the block is no longer valid for the rest of threads. This occurs for every iteration of the loop and as result the execution time is larger than the one obtained with the serial version. Another example of false sharing occurs in version `pi_par4`. However, this time it may only happen when the value of `priv_sum` is copied to the array `sum`. On the other hand, `pi_par3` still uses an array for storing the partial sums of each thread but avoids false sharing (discussed in the next paragraph). Finally, version `pi_par5` uses a private variable for storing the partial sums (`sum`) and after the calculation each thread adds the result to the shared variable `pi`. To avoid data races, that part of the code is encapsulated with the clause `critical` which ensures mutual exclusion between the threads.

The version `pi_par3` obtains the linesize of the cache to ensure that the positions of the array `sum` that are modified by each thread are located in different blocks. That is to say, the position modified by thread 1 will be placed in a different block than the position modified by thread 2 and so on. The small drawback is that we are allocating more memory than used: in each block (64 bytes), we are only using 8 bytes.

4.5 *What is the effect of using the pragma critical? How is the performance? Why does this happen?*

As mentioned before, this clause ensures mutual exclusion for an specific part of the code. This clause is used in