

# Arquitectura de ordenadores. Practice 3.

Pablo Cuesta Sierra, Álvaro Zamanillo Sáez  
(group 1392, team 04)

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**Note:** throughout this whole document, when we write “Matrix size ( $N$ )”, it means we are plotting (normally in the  $x$ -axis) the values of  $N$ , where  $N \times N$  is the size of the used matrices.

## Exercise 0: System cache

We have been submitting our tasks to the *MV* queue for all exercises of the practice because it returned the best (smoothest) results.

After running the commands shown in the statement, we got these results.

As can be seen in figure 1, the first level is the only one where there are two different caches: one for data and another for instructions. Both are of the same kind: size of 32768 B (32 KB), with blocks of 64 B and 8 ways. In the second level, there is a unique cache which is larger (2097152 B = 2 MB) but has the same degree of associativity. For the third level, the size increases (16777216 B = 16 MB) as well as the associativity (16 ways) whereas the block size remains the same.

```

LEVEL1_ICACHE_SIZE           32768
LEVEL1_ICACHE_ASSOC          8
LEVEL1_ICACHE_LINESIZE       64
LEVEL1_DCACHE_SIZE           32768
LEVEL1_DCACHE_ASSOC           8
LEVEL1_DCACHE_LINESIZE       64
LEVEL2_CACHE_SIZE            2097152
LEVEL2_CACHE_ASSOC            8
LEVEL2_CACHE_LINESIZE        64
LEVEL3_CACHE_SIZE            16777216
LEVEL3_CACHE_ASSOC            16
LEVEL3_CACHE_LINESIZE        64
LEVEL4_CACHE_SIZE             0
LEVEL4_CACHE_ASSOC            0
LEVEL4_CACHE_LINESIZE        0

```

Figure 1: Output of `getconf -a | grep -i cache`

Here is the info of each of the processors (this is processor 0, but they are all the same):

```

processor      : 0
vendor_id     : GenuineIntel
cpu family    : 6
model         : 26
model name    : Intel Core i7 9xx (Nehalem Class Core i7)
stepping      : 3
cpu MHz       : 2399.996
cache size    : 16384 KB
fpu           : yes
fpu_exception : yes
cpuid level   : 11
wp            : yes
flags         : fpu vme de pse tsc msr pae mce cx8 apic mtrr pge mca cmov pat pse36 clflush mmx
               fxsr sse sse2 syscall nx lm constant_tsc rep_good xtopology unfair_spinlock pni ssse3
               cx16 sse4_1 sse4_2 x2apic popcnt hypervisor lahf_lm
bogomips      : 4799.99
clflush size  : 64
cache_alignment : 64
address sizes : 46 bits physical, 48 bits virtual
power management:

```

Figure 2: First lines of `/proc/cpuinfo`

The following diagram shows the architecture of the different caches in each of the 8 cores.

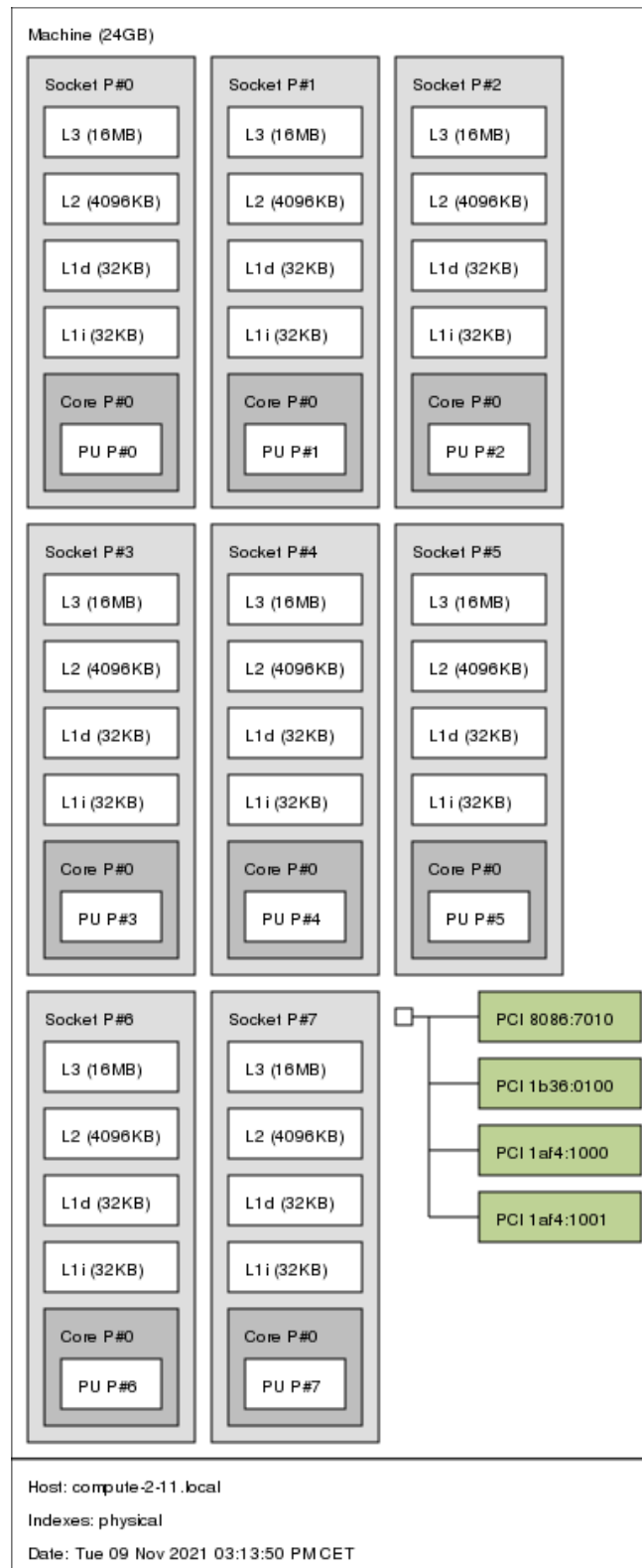


Figure 3: Topology of the used CPU.

## Exercise 1: Cache and performance

The following image shows a graph with the execution time of both programs for different sizes of the matrix.

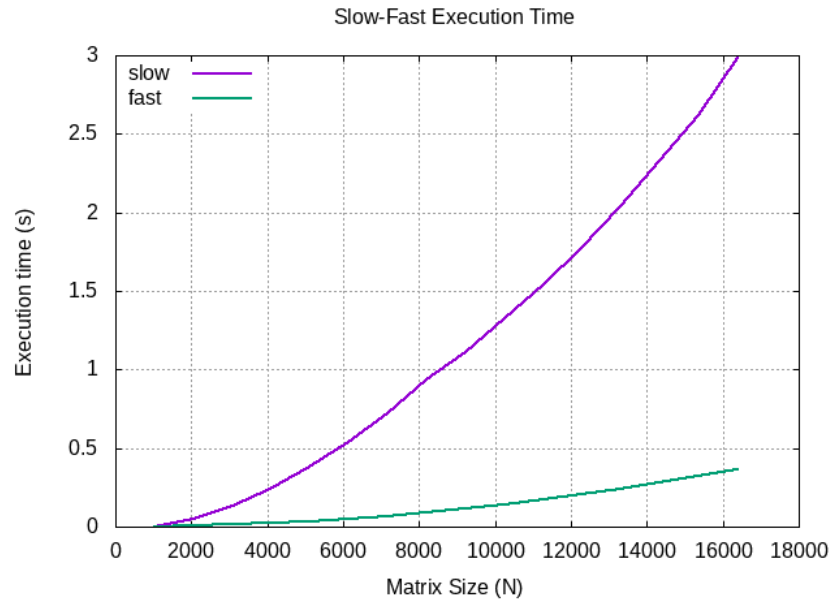


Figure 4: Slow vs Fast execution times.

As pointed by the graph, the execution time for small values of  $N$  is similar for both programs (most of the matrix can be stored completely in the cache). However, as  $N$  grows, the execution time for the slow program shows a significant increase while the fast version barely grows in comparison: for  $N = 16384$ , the execution time of *slow* is almost 10 times higher than that of *fast*.

This is due to the fact that the matrix is stored by rows in main memory and, therefore, the cache blocks will contain adjacent elements of single rows (although the last elements of a row may coincide in the same block as the first elements of the next row). The slow version access the matrix by columns which leads to a higher number of misses and, consequently, to a higher number of accesses to main memory (hundreds of times slower than access to cache).

For obtaining the results, it is necessary to run the simulation several times in order to calculate a mean and have more than one result, so that the programs do not present abnormal outliers because of other factors different from what we are measuring. We have repeated the tests 10 times for each  $N$ . Furthermore, the chosen execution pattern alternates between the slow and fast version to prevent the programs from reusing the cache from the previous execution (with the same size).

## Exercise 2: Cache size and performance

We are team 04, so for these tests we have used  $P = 4$ .

First, we will analyze the write misses:

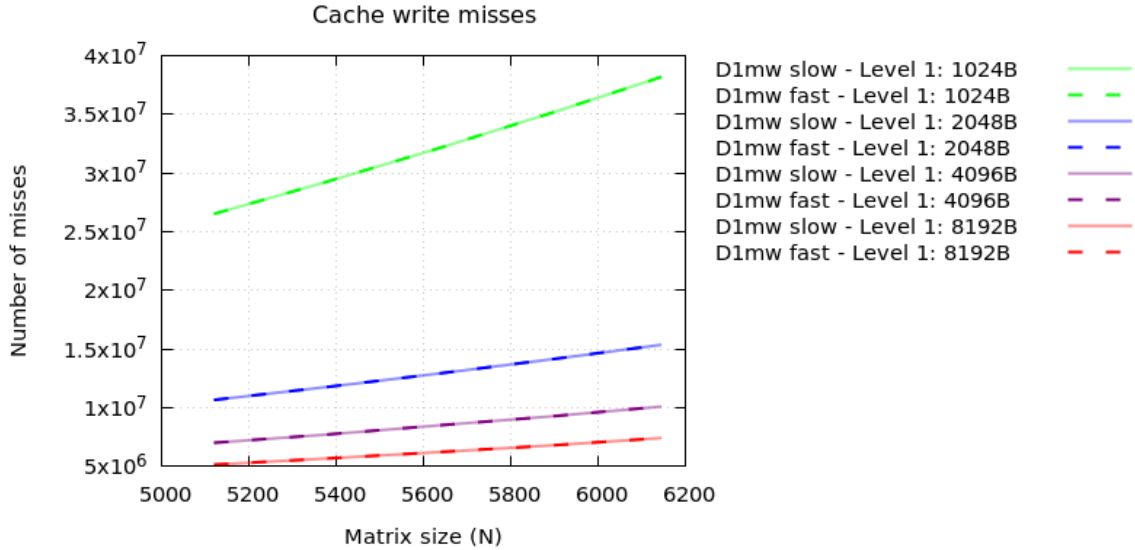


Figure 5: Cache write misses.

It may seem that only four lines have been plotted, however this is not the case. (We have plotted the *slow* graphs with a bit of transparency so that the *fast* graphs can also be seen). The slow and fast versions have (almost) the same number of write misses (for the same execution values of  $N$  and size of the cache). The reason behind this is that both programs fill (write) the initial matrix in the same way, by rows, using the function `generateMatrix(int size)`. The only other write operation that they perform is updating the value of variable `sum` (which occurs  $N^2 + 1$  times per program).

On the other hand, the read misses show different results:

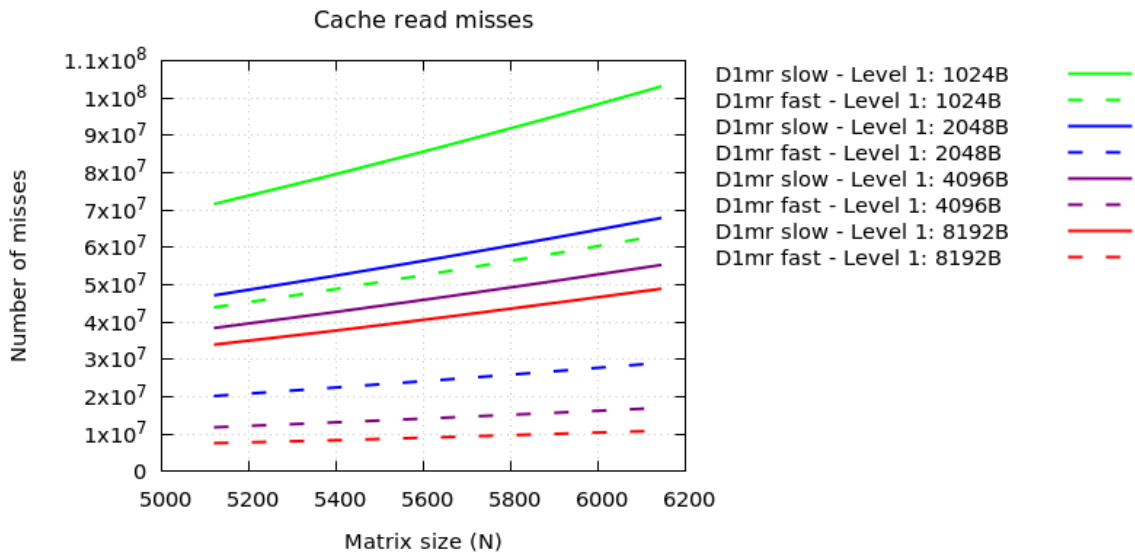


Figure 6: Cache read misses.

This time, we get 8 different lines, as one could expected beforehand. The dotted lines show the fast version, which necessarily must have less read misses than the slow one (when compared with the same cache size). Again, this is due to the fact that the matrix is stored by rows (one row beside the next, sequentially), and the slow version accesses the matrix by columns, while the fast version accesses it by rows. This means that the slow version uses a different block of the cache each time it reads an element of the matrix, not exploiting the fact that every block contains more than one element, and causing many more read misses.

In general, it is to be expected that smaller sized caches would provoke a higher number of misses for the same program; which is what we see in figure 6. The smaller the cache, the less likely the requested data will be present. The effect of the cache size can also be observed as the fast version for the smallest cache produces more misses than the slow version of the two largest caches.

### Exercise 3: Cache and matrix multiplication

The image below (figure 7) shows the execution time for the two different multiplication methods. The transposed multiplication is significantly faster as it accesses matrices by rows when multiplying. On the other hand, in the regular multiplication, the second operand matrix is accessed by columns which produces a higher rate of read misses and, as a result, a higher execution time.

Commenting on the strange peaks that appear in figure 7, we do not know the real reason why this happens. These peaks are neither because of some mistake on calculating values, nor inconsistencies in execution that could be solved repeating the tests. The values of over 10 seconds when executing for size  $N = 1408$  are pretty constant when executing in queue *mv.q* of the cluster (the same goes for the rest of the matrix sizes); meaning that the time in each iteration does not vary more than 0.1s for each  $N$ . If we execute the same script in another queue (*amd.q*, for instance), peaks still appear, but not necessarily in the same sizes ( $N$ ). We think this strange and counterintuitive behaviour might be caused by the fact that certain sizes of matrices are managed more efficiently by the cache (because its size is a multiple of the block size, for example) than others; even if these other ones are smaller.

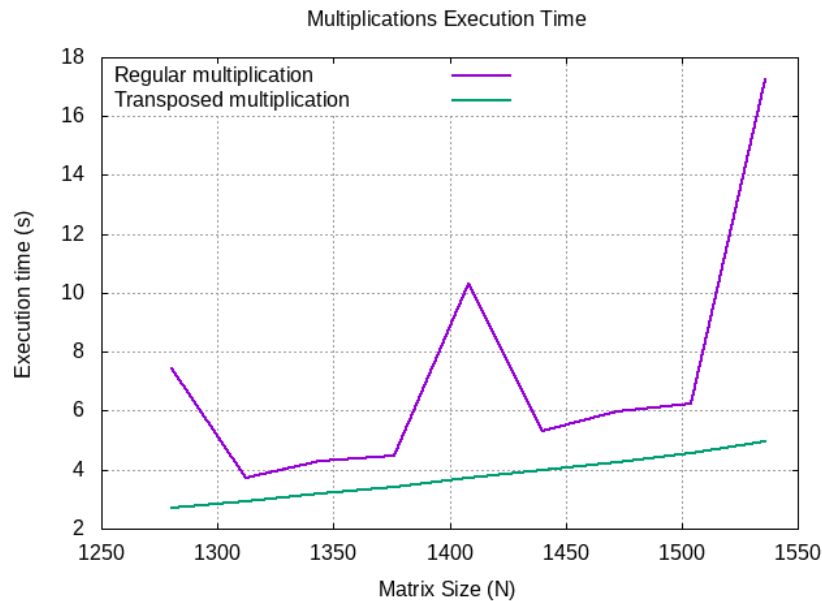


Figure 7: Multiplication execution time

When simulating with *valgrind* (figure 8), we get very similar results to what we saw in exercise 2 (figure 6). The less optimized program (regular multiplication), which reads matrix  $B$  by columns (instead of by rows), produces a higher number of read misses than the “transposed multiplication”, which accesses matrix  $B^t$  by rows.

The regular matrix multiplication shows a step pattern every two times we increase the value of  $N$ . This may be due to alignment of the data as we are increasing the matrix's  $N$  by 32 and the block size of the cache is 64B.

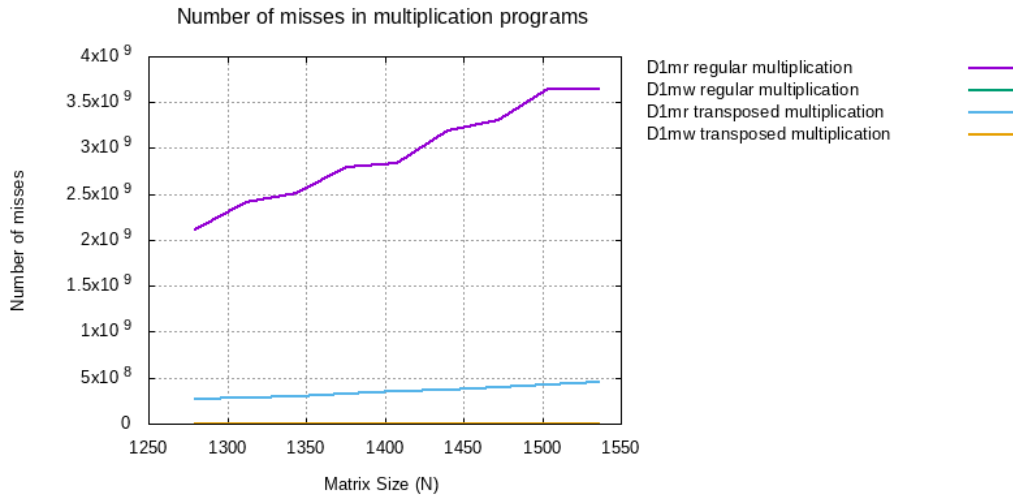


Figure 8: Cache misses of the multiplication programs

The write misses cannot be appreciated in figure 8, as they are much lower in value than the read misses, so we have plotted them in a separate graph (figure 9). Like in exercise 2, both programs write in the same manner: when generating matrices  $A$  and  $B$ , and when writing the result in matrix  $C = AB$ . So, as expected, the write misses are very similar. If we look closely at the exact numbers, we can see that the number of write misses is a bit higher (by less than 10 units) in the transposed version (for all sizes of the matrices). We think that this may happen because the transposed multiplication has to (re)write most of the values of matrix  $B$  when transposing it before multiplying.

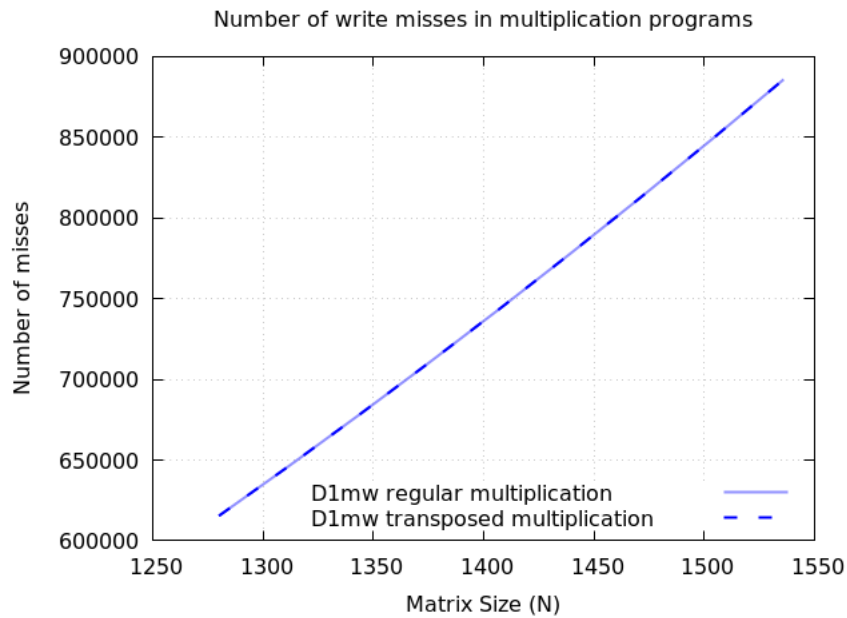


Figure 9: Cache write misses of the multiplication programs

## Exercise 4: Cache parameters in matrix multiplication

For this exercise, we have distinguished two main experiments. In each of them, we modify a different parameter of the cache, leaving the rest untouched. For both, as requested, we use the programs written for exercise 3: *multiplication.c* and *multiplication.t.c*

### Exercise 4. Experiment 1: Associativity

Here we simulate (using *valgrind*) the execution of both programs. We fix the line (block) size (64B), as well as the cache sizes: level 1 caches (both data and instructions caches) are of size 4kB, and level 2 cache is of size 8MB. For each experiment, we test with matrix sizes ( $N \times N$ ) for  $N \in \{3072, 3328, 3584, 3840, 4096\}$ . The difference between experiments is the type of set associative caches. We test for 1-way, 2-way and 8-way set associative caches.

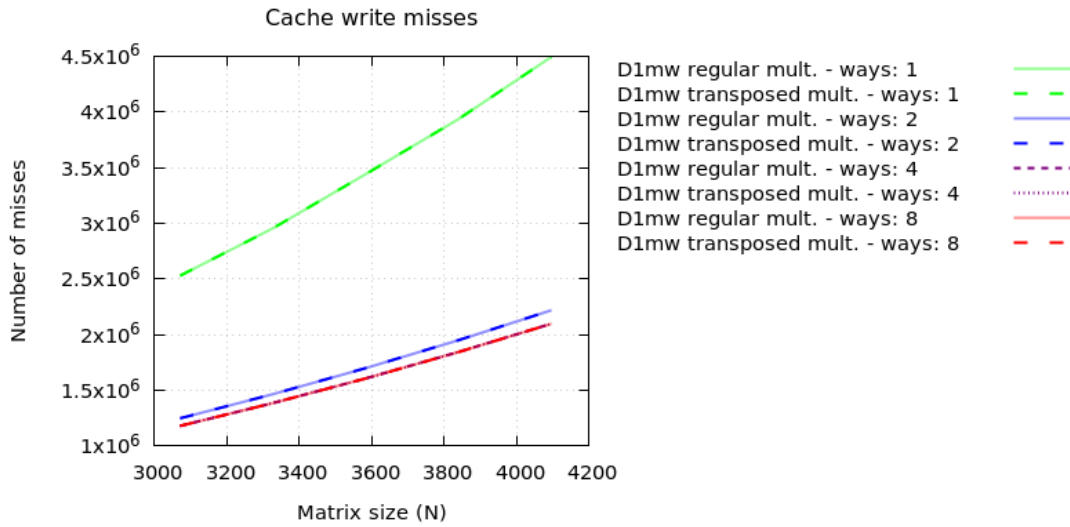


Figure 10: Cache write misses of the multiplication programs (varying associativity)

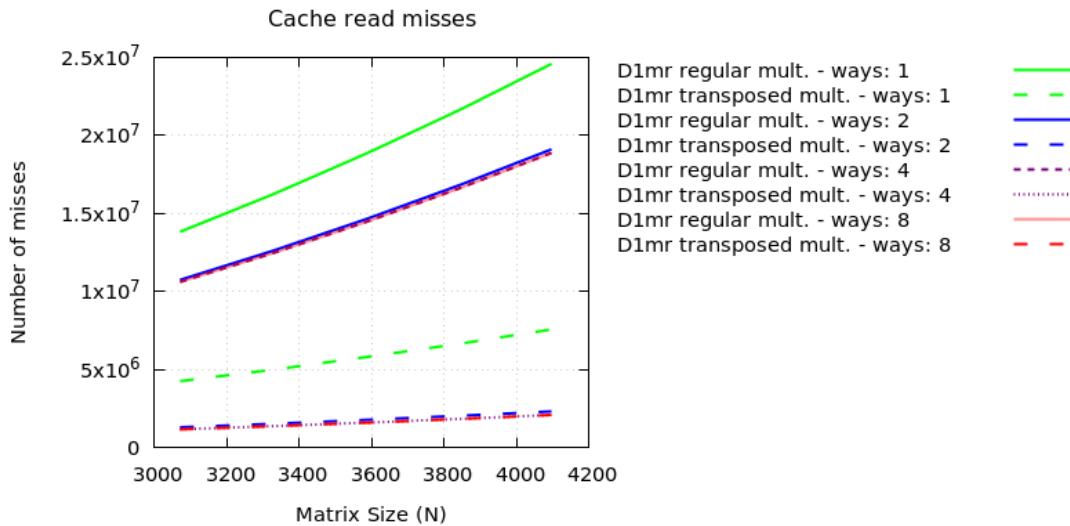


Figure 11: Cache read misses of the multiplication programs (varying associativity)



First of all, we will comment on the difference between both programs. Write misses (figure 10), for a fixed type of cache, are the same in both programs, as we already commented in exercise 3 (for figure 9). Read misses, on the other hand, are different. As could be expected, regular multiplication generates a much higher number of write misses than “transposed multiplication”. Again, this is due to the fact that transposed multiplication accesses both matrices by rows, which is how they are stored in memory; making it so that data accessed is always (when multiplying) next to the previous data which has been recently used; whereas regular multiplication traverses matrix  $B$  by columns, making “jumps” in memory, and making recently loaded blocks of the cache useless.

Next, let us take a look at the differences caused by the changes in associativity. There are three distinguished sections in our plots (already explained in last paragraph): cache write misses, cache read misses of regular multiplication, and cache read misses of transposed multiplication. In all of these sections, the 1-way cache generates the highest number of misses, followed by the 2-way cache; 4-way and 8-way cache yield almost the exact same numbers, which are very close below the 2-way cache’s.

These results do actually make sense, and are consistent with the performance explained in the theory slides. The line size of the caches is 64B, and there are  $\frac{4096}{64} = 64$  blocks in the (level 1) cache. Furthermore, each cache block contains 8 elements of a matrix (which means that, at a time, there cannot be more than 512 elements of a matrix in cache). Therefore, it is generally the case that a row fills several blocks. This means that when  $A$  is being multiplied by  $B$ , it frequently occurs (when calculating  $c_{ij} = \sum_{k=1}^N a_{ik}b_{kj}$ ) that the current block being used of  $A$  has the same index as the one being used from  $B$ . This implies that, if the cache is 1-way associative, the two current blocks will be replacing each other until one of them stops being used (which is known as conflict misses or collision misses); this causes the much higher number of misses for this kind of cache. However, when associativity increases, we no longer have the problem that the two current blocks rewrite each other in cache, so the number of misses decreases significantly.

#### Exercise 4. Experiment 2: Block size

For this second experiment, we are going to execute the two multiplication methods with caches of different sizes (2048B - 16384B) and see how the block size affects each time to the resulting misses. (The caches used in the simulations are all 1-way associative – direct mapped).

First of all, we are going to consider only read misses:

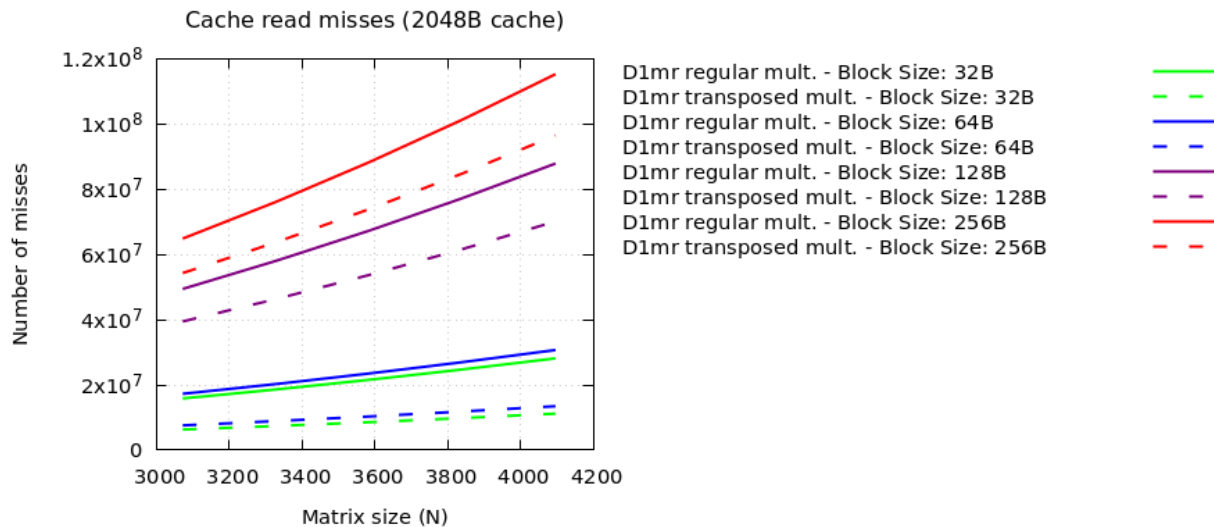


Figure 12: Cache read misses with a cache of 2048B

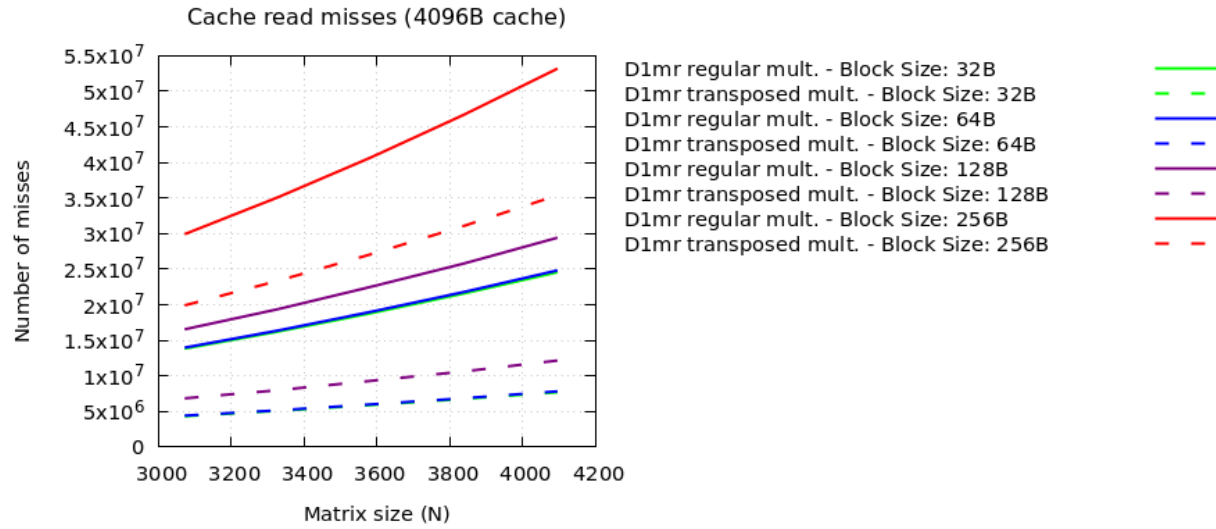


Figure 13: Cache read misses with a cache of 4096B

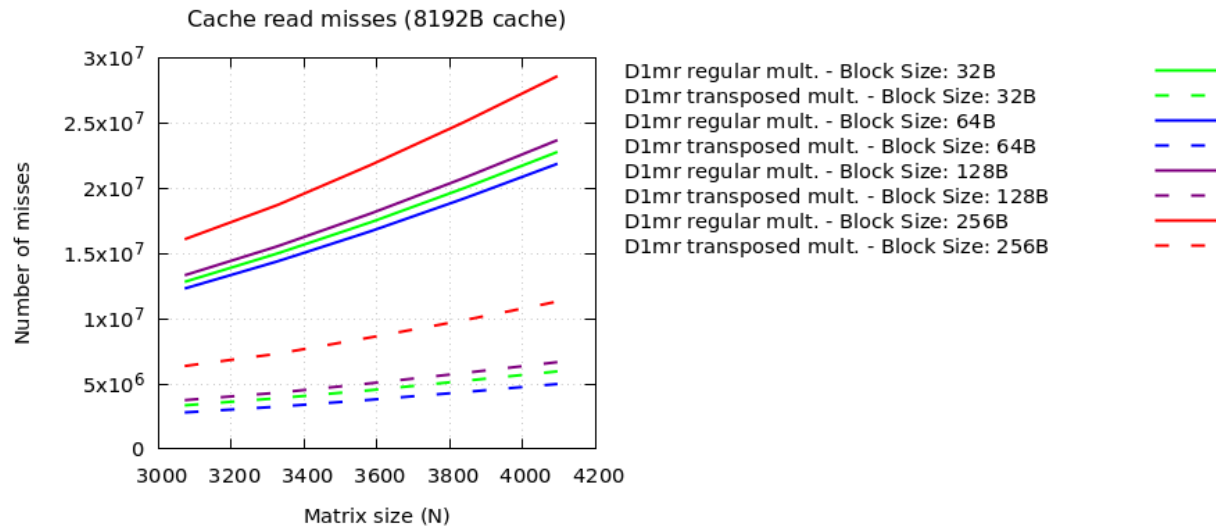


Figure 14: Cache read misses with a cache of 8192B

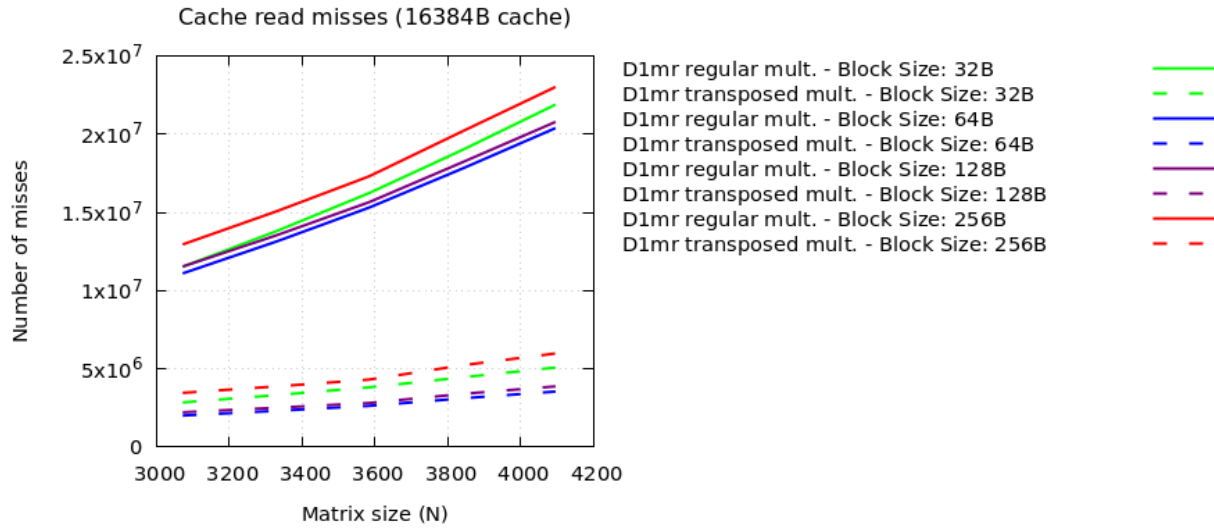


Figure 15: Cache read misses with a cache of 16384B

The first thing we notice is that as we increase the size of the cache, the lines for each block size configuration get closer (take for instance the case of a 16384B cache – figure 15). Therefore, it makes sense to think that the impact of the block size (for the regular multiplication) will be greater for small caches.

The key aspect is going to be the number of lines of the cache for each configuration. In order to determine this number, we have to do the following calculation:

$$\text{Number of lines} = \frac{\text{Cache Size}}{\text{Block Size}}$$

Let's focus now in the case of a 2048B cache. If we substitute the different values of the block size, we get these numbers of lines:

Block Size (B)	32	64	128	256
Number of lines	64	32	16	8

Table 1: Relation between block size and number of blocks for a 2048B cache.

When the block is 32 bytes long, we can store 4 elements of the matrix in each block (the type used in the matrix has a size of 8 bytes). In the case of regular multiplication, when obtaining the element  $c_{1,1}$ , for the first 8 multiplications, we have to fetch the first and second blocks of row 1 of matrix  $A$  and the first block of rows 1-8 of matrix  $B$ . As we have 64 rows, we have no need to replace. However, let see what happens when the block is of size 256B: we have only 8 lines in the cache. Again for calculating element  $c_{1,1}$  (first 8 multiplications) we first fetch the first block of row 1 of matrix  $A$ ; this time, the block contains 32 elements. Then we start fetching the beginning of the rows 1-8 of matrix  $B$ . As we only have 8 lines, we will have to replace at least once. And this example only contemplates the first 8 multiplications. However, the number of multiplications required for calculating each  $c_{ij}$  is  $N$ . And there are  $N^2$  elements per matrix.

So the problem in using big block sizes is that we limit the number of rows in the cache. Furthermore, it makes no sense having large blocks when doing the regular multiplication as we only need the first elements of each block. In other words, we are fetching huge blocks just to use a few bytes of them.

We could do the same analysis for the case of a 16384B cache. This time the number of lines when the block is 256B is 64, which is bigger than 32 (the number of elements that can be stored in a block). Thus, we are not getting the problem discussed above and the result does not differ much to the ones obtained with smaller values of the block size.

Now, we will look at write misses: Once again, we see that the number of write misses is the same for the regular and transpose multiplication as expected. The effect of the block size is similar to the one described for the read misses. The main idea is that when the cache is small and we use a large block, we reduce significantly the number of lines. Therefore, when multiplying both matrices and writing the result, there are going to be many replaces between the blocks used for calculation and the block used for writing the result. Just to illustrate this conflict, let's recall the case of a 2048B cache with 256B blocks. In this situation, the cache has 8 lines whose content alternates between part of the rows of the operands (which produces read misses) and part of the row of the result matrix (write misses). The scarcity of lines is what provokes a high rate of misses. Nonetheless, as we increase the size of the cache, the number of lines is “big” enough even if we use a block size of 256B (figure 19).

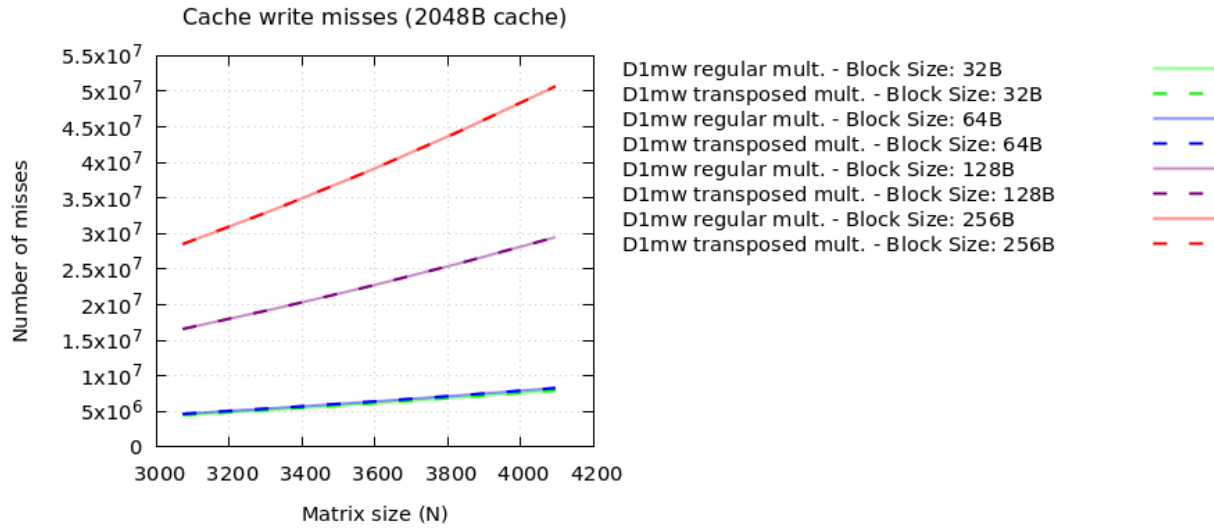


Figure 16: Cache write misses with a cache of 2048B

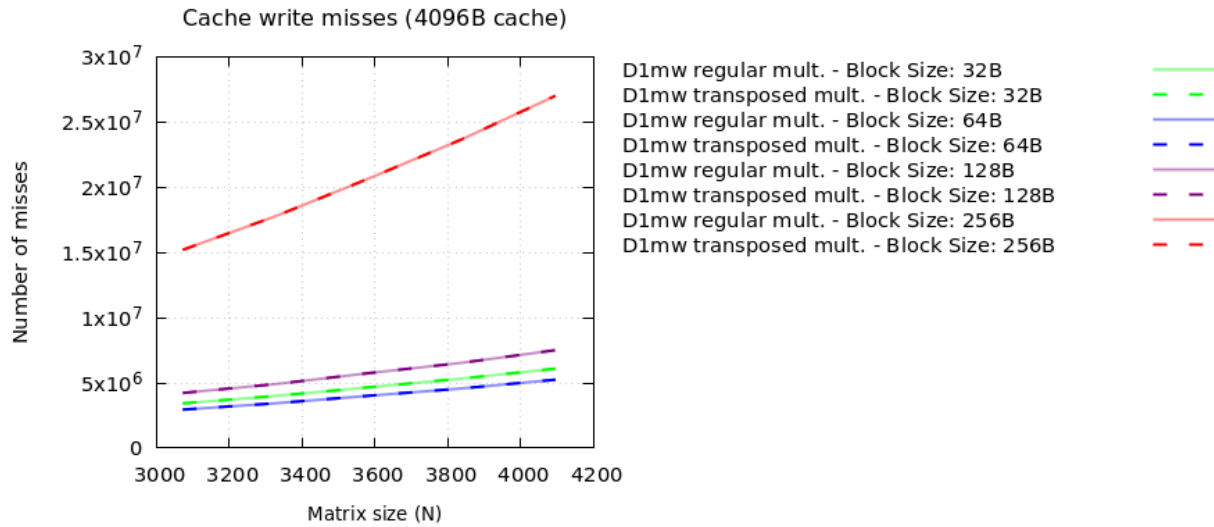


Figure 17: Cache write misses with a cache of 4096

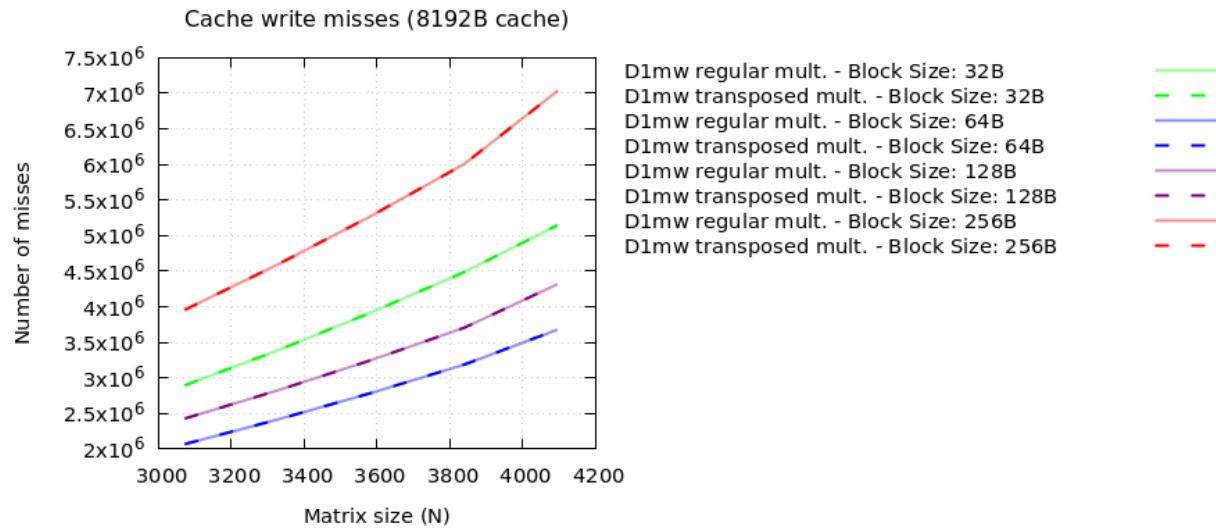


Figure 18: Cache write misses with a cache of 8192B

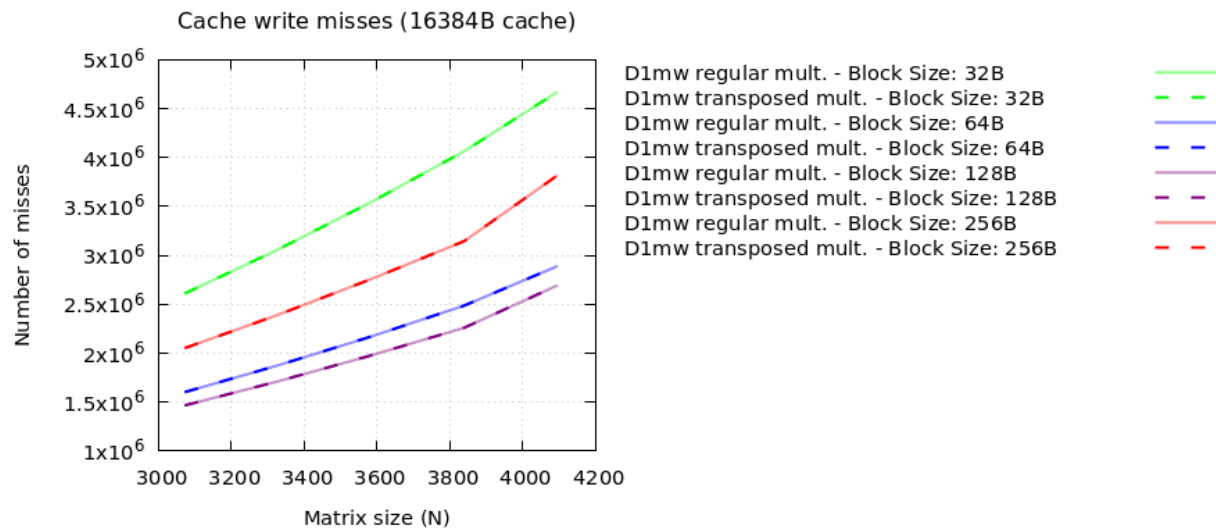


Figure 19: Cache write misses with a cache of 16384B)