Technical University of Denmark

F19
02346
DTU DIPLOM
DISTRIBUTED AND PARALLEL SYSTEMS

MANDATORY ASSIGNMENT 1

GRUPPE 17

21. FEBRUAR 2019

JOACHIM S. MORTENSEN
S175179

MIKAEL KRISTENSEN
S094766

NICOLAI KAMMERSGÅRD
S143780

Problem 1 (group): Clocks

Handed-in C File: ***timing.c***

We implemented the different types of clocks in the 3 given methods and tested each clock method 2 times, with 1000*1000 operations and 1000000*1000000 operations, we got the following elapsed time:

1000*1000 operations, elapsed time in seconds:

gettimeofday	0.00478887557983398437500000000000000000000000000000
clock_gettime(CLOCK_REALTIME)	0.00323939323425292968750000000000000000000000000000
clock_gettime(CLOCK_MONOTONIC)	0.00315925013273954391479492187500000000000000000000

Estimated resolution in nanoseconds:

gettimeofday	4.788875580
clock_gettime(CLOCK_REALTIME)	3.239393234
clock_gettime(CLOCK_MONOTONIC)	3.159250133

10000*10000 operations, elapsed time in seconds:

gettimeofday	0.28973507881164550781250000000000000000000000000000
clock_gettime(CLOCK_REALTIME)	0.28063416481018066406250000000000000000000000000000
clock_gettime(CLOCK_MONOTONIC)	0.28096101293340325355529785156250000000000000000000

Estimated resolution in nanoseconds:

gettimeofday	2.897350788
clock_gettime(CLOCK_REALTIME)	2.806341648
clock_gettime(CLOCK_MONOTONIC)	2.809610129

So what we see is we get an resolution going towards 2ns. We can get the actual resolution for the two clocks of clock_gettime by using the method clock_getres. This gives us a resolution of 1 nanosecond. This is a hardcoded value as these clocks are "high-resolution". A clock that isn't high resolution would return 1/Hz instead. as we can see the estimate is a bit off, but actually quite close.

Which timing function would you suggest to use? gettimeofday is marked as obsolete and clock_gettime is there as its successor and recommended to use instead. With regards to clock_gettime, we would rather use the id CLOCK_MONOTONIC is the more reliable clock as it increases linearly while the clock CLOCK_REALTIME has a chance of leaping forward or backwards and can be set by the function clock_settime.

What do the compiler options -O0 -lrt mean? -O0 removes a large number of optimisation passes.
-lrt specifies that we want to link with the "rt"library, as -l tells the compiler to link with the library name that follows.

How would you expect the timing to behave with varying workload if the clock had a resolution of say 100 μs (microseconds)? Did you see any such effect in your experiments? If not, why not so? The less accurate the clock the larger the workload has to be to get an accurate timing. We can see this our estimate with gettimeofday, as this clock is far less accurate than either of the other two timing functions, so the estimate on small workloads is more off compared to the other two. As the workload increases the accuracy of our estimate does as well, as shown in the $10000 * 10000$ example where the gettimeofday clock is fairly accurate.

Problem 2 (group): Cache performance

Handed-in C File: ***cachetest.c, matrix_sum.c***

In Appendix A and Appendix B we see the different runs of cache test with different timing functions. Appendix B uses the given get_seconds method which relies on cpu cycles and counting how many of them have gone by. Appendix A uses the clock_gettime with the clock id CLOCK_MONOTONIC_RAW, which we met in execise 1.4. Comparing the to runs, we see that the read+write time have a bigger variance when using clock cycles rather than the clock_gettime. The variance makes it harder to spot the switches between caches, why the clock_gettime is preferable for spotting cache misses.

The file cachetest.c contains 2 do-while loops. The first do while loop runs for half a second and tries to make as many access to memory as possible in this timeframe. the memory spaces which are accessed are offset by the stride value. Then the second do while makes the same amount of operations as the first do while, specified by the "steps"variable, but this time does not access memory but the dummy value from the register. This gives us the overhead time, and if we subtract the runtime of the second do while from the first we get the actual time taken to read/write to memory. This time in nanoseconds is what is printed in the read+write column.

Many of the variables have the "register"keyword in their definitions which suggests to the compiler that the variable will be heavily used and accessed so keeping it in a register would be a good idea so the processor doesn't have to constantly fetch the value of the variables from memory. This reduces the runtime of the program drastically.

In Appendix A we see the output from 1 run of the cachetest file. In this output we can see from line 1 to 40 a read+write time of under 0.5ns. Once the cache size increases to 64KB we have an increase in read+write time, as the whole dataset can no longer be loaded into the L1 cache at the same time. This means that the L1 cache should be around 32KB.
The cache-misses seem to start when we stride 64 bytes. This tells us that the cache line size is about 64 bytes as we keep missing.

We see the same pattern occuring again at a cache size of around 32MB where the the read+write time goes from around 2-3ns i L2 cache to around 4-9ns. This should mean that we now have gone from the L2 cache to either L3 or main memory, and that the L2 cache is of size 16MB. We believe that there are three levels of cache as accessing the main memory would take much longer than the 10ns we get when we miss our L2 cache size.

Summing Matrices and the impact of caching
Running the two sum functions clearly shows that sum1 which iterates over each column in each row in succession, is way better performing than the sum2 function, which does the opposite (iterates over each row in each column in succession). sum1 is faster than sum2 by around a factor 8 because of the way arrays are stored in memory. sum1 runs through memory sequentially while sum2 takes big strides in memory locations, leading to a lot of cache misses. The smaller the matrix the less impact this has as we will get less and less cache misses.

How do you need to write your programs to suit the memory hierarchy? To maximize performance when accessing memory one should try to optimize ones data structure so that the accessing can happen sequentially.

Problem 3 (individual): Java vs C

s094766

C is a function language which means that the need for breaking code into functions is quite important, since there is no possibility to define functionality in different classes and reference it as objects.

Java is compiled into java bytecode while C is compiled into assembly.

Java works with references which gives some degree of access to memory, however in C we have full access to memory, while being able to manipulate the reference/pointer. This gives many more possibilities in how you can reference memory spaces, however comes with way more responsibility.

Java runs its bytecode on a virtual machine, a layer of abstraction between the processor and the code.

Java has a garbage collector that takes care of memory management for you, whereas in C you are fully responsible for cleaning your memory usage.

Problem 4 (individual): MSI Cache Protocol

s143780

The different steps is shown below.

	M	Mb	C1	C1s	C2	C2s
Step 0	x=5	null	null	I	null	I
Step 1a	x=5	BusRd	null	I	null	I
Step 1b	x=5	null	x=5	S	null	I
Step 2a	x=5	BusRd	x=5	S	null	I
Step 2b	x=5	null	x=5	S	x=5	S
Step 3a	x=5	BusUpgr	x=5	S	x=5	S
Step 3b	x=5	null	x=6	M	null	I
Step 4a	x=5	null	x=6	M	null	I
Step 5a	x=5	BusRdX	x=6	M	null	I
Step 5b	x=6	null	null	I	x=6	M
Step 5c	x=6	null	null	I	x=8	M
Step 6a	x=6	BusRd	null	I	x=8	M
Step 6b	x=8	null	x=8	S	x=8	S

A pro of using the MSI Cache protocol is that you ensure that the data is aligned across caches, and therefore can scale the access to same memory locations quite well. A con is that it takes a lot of traffic on the bus to keep this data coherence. The MOSI, MESI and MOESI protocols solve some of this extra traffic by adding more states.

Problem 5 (individual): Omega switching network

s175179

1. State which mode setting would be needed for a message to be sent from processor 0 to memory module 6? (1A crossed, . . .)
To get to module 6 from CPU0, the switch 1A has to be in crossed mode, the switch 2B has to be in straight mode and finally the switch 3C in crossed mode.

2. State which mode setting would be needed for a message to be sent from processor 6 to memory module 2?
To get to module 2 from CPU6, the switch 1B has to be in crossed mode, the switch 2C has to be in straight mode and finally the switch 3A in straight mode.

3. Given these settings, would be be possible to send a message from processor 2 to memory module 5?
Yes, it is possible if switch 2D is also in straight mode. See appendix C

4. Again given the settings of 1. and 2., which memory modules can be reached from processor 1?
Memory bank 6, 7 and 8 can be reached from CPU1 with the given settings.

5. If all switches are set straight, how does the network connect processors and memory modules?
1 to 1, 2 to 2, 3 to 3 etc. See Appendix D.

6. Is it possible to connect processor no. i with memory module (i+1) mod 8 for all processors at the same time?
Yes it is possible when the switches are configured as follows:
1A straight, 1B straight, 1C straight, 1D crossed.
2A straight, 2B straight, 2C crossed, 2D crossed.
3A crossed, 3B crossed, 3C crossed, 3D crossed.
See Appendix E.

Appendix A - CacheTest run on n-62-27-23

```
Size (bytes): 4096, Stride (bytes): 4, read+write: 0.32 ns (steps: 499)
Size (bytes): 4096, Stride (bytes): 8, read+write: 0.30 ns (steps: 503)
Size (bytes): 4096, Stride (bytes): 16, read+write: 0.29 ns (steps: 498)
Size (bytes): 4096, Stride (bytes): 32, read+write: 0.26 ns (steps: 492)
Size (bytes): 4096, Stride (bytes): 64, read+write: 0.20 ns (steps: 464)
Size (bytes): 4096, Stride (bytes): 128, read+write: 0.26 ns (steps: 378)
Size (bytes): 4096, Stride (bytes): 256, read+write: 0.35 ns (steps: 375)
Size (bytes): 4096, Stride (bytes): 512, read+write: 0.32 ns (steps: 382)
Size (bytes): 4096, Stride (bytes):1024, read+write: 0.66 ns (steps: 380)
Size (bytes): 8192, Stride (bytes): 4, read+write: 0.31 ns (steps: 508)
Size (bytes): 8192, Stride (bytes): 8, read+write: 0.31 ns (steps: 507)
Size (bytes): 8192, Stride (bytes): 16, read+write: 0.29 ns (steps: 503)
Size (bytes): 8192, Stride (bytes): 32, read+write: 0.28 ns (steps: 499)
Size (bytes): 8192, Stride (bytes): 64, read+write: 0.25 ns (steps: 494)
Size (bytes): 8192, Stride (bytes): 128, read+write: 0.20 ns (steps: 471)
Size (bytes): 8192, Stride (bytes): 256, read+write: 0.24 ns (steps: 384)
Size (bytes): 8192, Stride (bytes): 512, read+write: 0.33 ns (steps: 380)
Size (bytes): 8192, Stride (bytes):1024, read+write: 0.33 ns (steps: 377)
Size (bytes): 16384, Stride (bytes): 4, read+write: 0.32 ns (steps: 499)
Size (bytes): 16384, Stride (bytes): 8, read+write: 0.32 ns (steps: 502)
Size (bytes): 16384, Stride (bytes): 16, read+write: 0.30 ns (steps: 507)
Size (bytes): 16384, Stride (bytes): 32, read+write: 0.29 ns (steps: 506)
Size (bytes): 16384, Stride (bytes): 64, read+write: 0.29 ns (steps: 494)
Size (bytes): 16384, Stride (bytes): 128, read+write: 0.24 ns (steps: 492)
Size (bytes): 16384, Stride (bytes): 256, read+write: 0.19 ns (steps: 472)
Size (bytes): 16384, Stride (bytes): 512, read+write: 0.25 ns (steps: 377)
Size (bytes): 16384, Stride (bytes):1024, read+write: 0.34 ns (steps: 373)
Size (bytes): 32768, Stride (bytes): 4, read+write: 0.33 ns (steps: 497)
Size (bytes): 32768, Stride (bytes): 8, read+write: 0.32 ns (steps: 497)
Size (bytes): 32768, Stride (bytes): 16, read+write: 0.32 ns (steps: 496)
Size (bytes): 32768, Stride (bytes): 32, read+write: 0.32 ns (steps: 496)
Size (bytes): 32768, Stride (bytes): 64, read+write: 0.32 ns (steps: 491)
Size (bytes): 32768, Stride (bytes): 128, read+write: 0.30 ns (steps: 484)
Size (bytes): 32768, Stride (bytes): 256, read+write: 0.30 ns (steps: 458)
Size (bytes): 32768, Stride (bytes): 512, read+write: 0.31 ns (steps: 422)
Size (bytes): 32768, Stride (bytes):1024, read+write: 0.31 ns (steps: 365)
Size (bytes): 65536, Stride (bytes): 4, read+write: 0.32 ns (steps: 502)
Size (bytes): 65536, Stride (bytes): 8, read+write: 0.31 ns (steps: 507)
Size (bytes): 65536, Stride (bytes): 16, read+write: 0.32 ns (steps: 509)
Size (bytes): 65536, Stride (bytes): 32, read+write: 0.39 ns (steps: 468)
Size (bytes): 65536, Stride (bytes): 64, read+write: 1.41 ns (steps: 238)
Size (bytes): 65536, Stride (bytes): 128, read+write: 1.42 ns (steps: 236)
Size (bytes): 65536, Stride (bytes): 256, read+write: 1.45 ns (steps: 230)
Size (bytes): 65536, Stride (bytes): 512, read+write: 1.37 ns (steps: 233)
Size (bytes): 65536, Stride (bytes):1024, read+write: 2.76 ns (steps: 137)
Size (bytes): 131072, Stride (bytes): 4, read+write: 0.33 ns (steps: 498)
Size (bytes): 131072, Stride (bytes): 8, read+write: 0.33 ns (steps: 498)
Size (bytes): 131072, Stride (bytes): 16, read+write: 0.33 ns (steps: 496)
```

Size (bytes): 131072, Stride (bytes): 32, read+write: 0.42 ns (steps: 457)
Size (bytes): 131072, Stride (bytes): 64, read+write: 1.45 ns (steps: 235)
Size (bytes): 131072, Stride (bytes): 128, read+write: 1.47 ns (steps: 232)
Size (bytes): 131072, Stride (bytes): 256, read+write: 1.44 ns (steps: 235)
Size (bytes): 131072, Stride (bytes): 512, read+write: 1.39 ns (steps: 237)
Size (bytes): 131072, Stride (bytes):1024, read+write: 2.80 ns (steps: 141)
Size (bytes): 262144, Stride (bytes): 4, read+write: 0.32 ns (steps: 506)
Size (bytes): 262144, Stride (bytes): 8, read+write: 0.31 ns (steps: 508)
Size (bytes): 262144, Stride (bytes): 16, read+write: 0.39 ns (steps: 472)
Size (bytes): 262144, Stride (bytes): 32, read+write: 0.74 ns (steps: 356)
Size (bytes): 262144, Stride (bytes): 64, read+write: 1.90 ns (steps: 195)
Size (bytes): 262144, Stride (bytes): 128, read+write: 1.91 ns (steps: 193)
Size (bytes): 262144, Stride (bytes): 256, read+write: 1.90 ns (steps: 194)
Size (bytes): 262144, Stride (bytes): 512, read+write: 1.72 ns (steps: 207)
Size (bytes): 262144, Stride (bytes):1024, read+write: 2.94 ns (steps: 136)
Size (bytes): 524288, Stride (bytes): 4, read+write: 0.32 ns (steps: 509)
Size (bytes): 524288, Stride (bytes): 8, read+write: 0.33 ns (steps: 503)
Size (bytes): 524288, Stride (bytes): 16, read+write: 0.44 ns (steps: 455)
Size (bytes): 524288, Stride (bytes): 32, read+write: 1.05 ns (steps: 291)
Size (bytes): 524288, Stride (bytes): 64, read+write: 2.35 ns (steps: 166)
Size (bytes): 524288, Stride (bytes): 128, read+write: 2.58 ns (steps: 154)
Size (bytes): 524288, Stride (bytes): 256, read+write: 2.64 ns (steps: 151)
Size (bytes): 524288, Stride (bytes): 512, read+write: 2.25 ns (steps: 171)
Size (bytes): 524288, Stride (bytes):1024, read+write: 2.38 ns (steps: 163)
Size (bytes): 1048576, Stride (bytes): 4, read+write: 0.32 ns (steps: 501)
Size (bytes): 1048576, Stride (bytes): 8, read+write: 0.31 ns (steps: 507)
Size (bytes): 1048576, Stride (bytes): 16, read+write: 0.44 ns (steps: 452)
Size (bytes): 1048576, Stride (bytes): 32, read+write: 1.05 ns (steps: 291)
Size (bytes): 1048576, Stride (bytes): 64, read+write: 2.36 ns (steps: 165)
Size (bytes): 1048576, Stride (bytes): 128, read+write: 2.63 ns (steps: 152)
Size (bytes): 1048576, Stride (bytes): 256, read+write: 2.79 ns (steps: 145)
Size (bytes): 1048576, Stride (bytes): 512, read+write: 2.22 ns (steps: 173)
Size (bytes): 1048576, Stride (bytes):1024, read+write: 2.40 ns (steps: 163)
Size (bytes): 2097152, Stride (bytes): 4, read+write: 0.32 ns (steps: 506)
Size (bytes): 2097152, Stride (bytes): 8, read+write: 0.32 ns (steps: 502)
Size (bytes): 2097152, Stride (bytes): 16, read+write: 0.43 ns (steps: 455)
Size (bytes): 2097152, Stride (bytes): 32, read+write: 1.04 ns (steps: 292)
Size (bytes): 2097152, Stride (bytes): 64, read+write: 2.39 ns (steps: 164)
Size (bytes): 2097152, Stride (bytes): 128, read+write: 2.67 ns (steps: 150)
Size (bytes): 2097152, Stride (bytes): 256, read+write: 2.83 ns (steps: 144)
Size (bytes): 2097152, Stride (bytes): 512, read+write: 2.24 ns (steps: 172)
Size (bytes): 2097152, Stride (bytes):1024, read+write: 2.41 ns (steps: 163)
Size (bytes): 4194304, Stride (bytes): 4, read+write: 0.33 ns (steps: 504)
Size (bytes): 4194304, Stride (bytes): 8, read+write: 0.33 ns (steps: 503)
Size (bytes): 4194304, Stride (bytes): 16, read+write: 0.42 ns (steps: 458)
Size (bytes): 4194304, Stride (bytes): 32, read+write: 1.04 ns (steps: 292)
Size (bytes): 4194304, Stride (bytes): 64, read+write: 2.39 ns (steps: 164)
Size (bytes): 4194304, Stride (bytes): 128, read+write: 2.66 ns (steps: 151)
Size (bytes): 4194304, Stride (bytes): 256, read+write: 2.81 ns (steps: 144)
Size (bytes): 4194304, Stride (bytes): 512, read+write: 2.23 ns (steps: 173)

Size (bytes): 4194304, Stride (bytes):1024, read+write: 2.53 ns (steps: 156)
Size (bytes): 8388608, Stride (bytes): 4, read+write: 0.32 ns (steps: 501)
Size (bytes): 8388608, Stride (bytes): 8, read+write: 0.32 ns (steps: 504)
Size (bytes): 8388608, Stride (bytes): 16, read+write: 0.43 ns (steps: 453)
Size (bytes): 8388608, Stride (bytes): 32, read+write: 1.04 ns (steps: 292)
Size (bytes): 8388608, Stride (bytes): 64, read+write: 2.37 ns (steps: 166)
Size (bytes): 8388608, Stride (bytes): 128, read+write: 2.67 ns (steps: 150)
Size (bytes): 8388608, Stride (bytes): 256, read+write: 2.83 ns (steps: 143)
Size (bytes): 8388608, Stride (bytes): 512, read+write: 2.25 ns (steps: 172)
Size (bytes): 8388608, Stride (bytes):1024, read+write: 2.78 ns (steps: 145)
Size (bytes): 16777216, Stride (bytes): 4, read+write: 0.33 ns (steps: 505)
Size (bytes): 16777216, Stride (bytes): 8, read+write: 0.32 ns (steps: 507)
Size (bytes): 16777216, Stride (bytes): 16, read+write: 0.43 ns (steps: 458)
Size (bytes): 16777216, Stride (bytes): 32, read+write: 1.05 ns (steps: 293)
Size (bytes): 16777216, Stride (bytes): 64, read+write: 2.36 ns (steps: 166)
Size (bytes): 16777216, Stride (bytes): 128, read+write: 2.68 ns (steps: 150)
Size (bytes): 16777216, Stride (bytes): 256, read+write: 2.84 ns (steps: 142)
Size (bytes): 16777216, Stride (bytes): 512, read+write: 2.25 ns (steps: 171)
Size (bytes): 16777216, Stride (bytes):1024, read+write: 3.03 ns (steps: 136)
Size (bytes): 33554432, Stride (bytes): 4, read+write: 0.36 ns (steps: 488)
Size (bytes): 33554432, Stride (bytes): 8, read+write: 0.41 ns (steps: 461)
Size (bytes): 33554432, Stride (bytes): 16, read+write: 0.85 ns (steps: 330)
Size (bytes): 33554432, Stride (bytes): 32, read+write: 2.04 ns (steps: 185)
Size (bytes): 33554432, Stride (bytes): 64, read+write: 4.67 ns (steps: 94)
Size (bytes): 33554432, Stride (bytes): 128, read+write: 6.01 ns (steps: 75)
Size (bytes): 33554432, Stride (bytes): 256, read+write: 6.16 ns (steps: 74)
Size (bytes): 33554432, Stride (bytes): 512, read+write: 5.63 ns (steps: 80)
Size (bytes): 33554432, Stride (bytes):1024, read+write: 5.92 ns (steps: 76)
Size (bytes): 67108864, Stride (bytes): 4, read+write: 0.38 ns (steps: 479)
Size (bytes): 67108864, Stride (bytes): 8, read+write: 0.47 ns (steps: 440)
Size (bytes): 67108864, Stride (bytes): 16, read+write: 1.06 ns (steps: 290)
Size (bytes): 67108864, Stride (bytes): 32, read+write: 2.60 ns (steps: 154)
Size (bytes): 67108864, Stride (bytes): 64, read+write: 5.98 ns (steps: 76)
Size (bytes): 67108864, Stride (bytes): 128, read+write: 8.38 ns (steps: 56)
Size (bytes): 67108864, Stride (bytes): 256, read+write: 9.46 ns (steps: 50)
Size (bytes): 67108864, Stride (bytes): 512, read+write: 8.94 ns (steps: 53)
Size (bytes): 67108864, Stride (bytes):1024, read+write: 9.10 ns (steps: 52)
Size (bytes):134217728, Stride (bytes): 4, read+write: 0.39 ns (steps: 475)
Size (bytes):134217728, Stride (bytes): 8, read+write: 0.47 ns (steps: 441)
Size (bytes):134217728, Stride (bytes): 16, read+write: 1.05 ns (steps: 292)
Size (bytes):134217728, Stride (bytes): 32, read+write: 2.61 ns (steps: 153)
Size (bytes):134217728, Stride (bytes): 64, read+write: 6.01 ns (steps: 75)
Size (bytes):134217728, Stride (bytes): 128, read+write: 8.44 ns (steps: 55)
Size (bytes):134217728, Stride (bytes): 256, read+write: 9.56 ns (steps: 49)
Size (bytes):134217728, Stride (bytes): 512, read+write: 8.93 ns (steps: 53)
Size (bytes):134217728, Stride (bytes):1024, read+write: 9.16 ns (steps: 51)

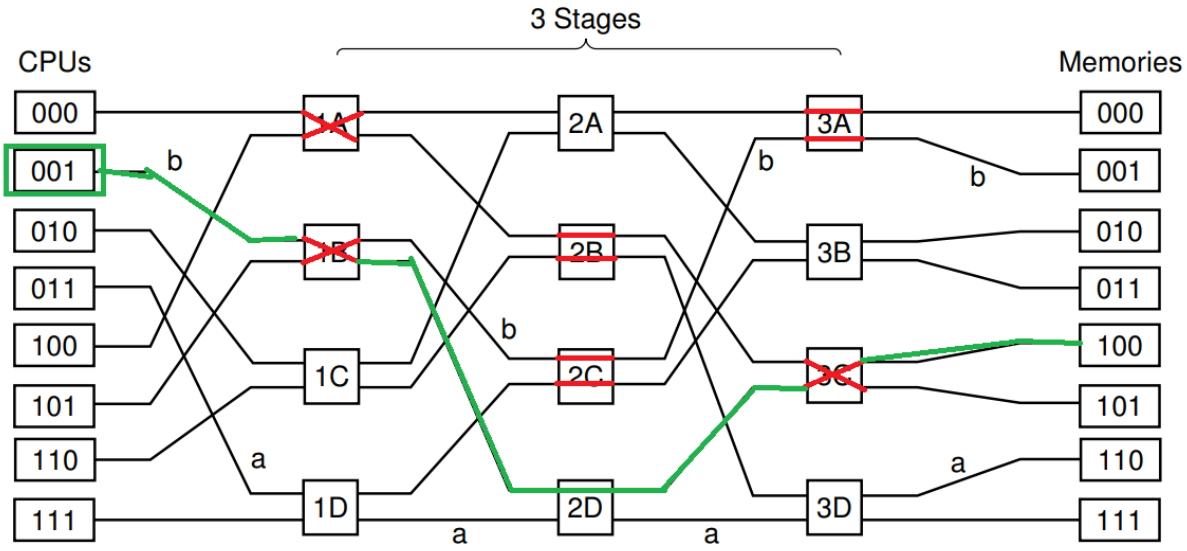
Appendix B - CacheTest run on n-62-27-23

```
Size (bytes): 4096, Stride (bytes): 4, read+write: 0.76 ns (steps: 238)
Size (bytes): 4096, Stride (bytes): 8, read+write: 0.81 ns (steps: 235)
Size (bytes): 4096, Stride (bytes): 16, read+write: 0.84 ns (steps: 225)
Size (bytes): 4096, Stride (bytes): 32, read+write: 0.83 ns (steps: 217)
Size (bytes): 4096, Stride (bytes): 64, read+write: 0.77 ns (steps: 207)
Size (bytes): 4096, Stride (bytes): 128, read+write: 0.80 ns (steps: 175)
Size (bytes): 4096, Stride (bytes): 256, read+write: 0.70 ns (steps: 172)
Size (bytes): 4096, Stride (bytes): 512, read+write: 0.76 ns (steps: 172)
Size (bytes): 4096, Stride (bytes):1024, read+write: 0.73 ns (steps: 179)
Size (bytes): 8192, Stride (bytes): 4, read+write: 0.80 ns (steps: 237)
Size (bytes): 8192, Stride (bytes): 8, read+write: 0.86 ns (steps: 233)
Size (bytes): 8192, Stride (bytes): 16, read+write: 0.82 ns (steps: 231)
Size (bytes): 8192, Stride (bytes): 32, read+write: 0.85 ns (steps: 224)
Size (bytes): 8192, Stride (bytes): 64, read+write: 0.84 ns (steps: 214)
Size (bytes): 8192, Stride (bytes): 128, read+write: 0.83 ns (steps: 205)
Size (bytes): 8192, Stride (bytes): 256, read+write: 0.93 ns (steps: 172)
Size (bytes): 8192, Stride (bytes): 512, read+write: 0.70 ns (steps: 171)
Size (bytes): 8192, Stride (bytes):1024, read+write: 0.68 ns (steps: 177)
Size (bytes): 16384, Stride (bytes): 4, read+write: 0.86 ns (steps: 233)
Size (bytes): 16384, Stride (bytes): 8, read+write: 0.86 ns (steps: 233)
Size (bytes): 16384, Stride (bytes): 16, read+write: 0.87 ns (steps: 229)
Size (bytes): 16384, Stride (bytes): 32, read+write: 0.88 ns (steps: 227)
Size (bytes): 16384, Stride (bytes): 64, read+write: 0.86 ns (steps: 221)
Size (bytes): 16384, Stride (bytes): 128, read+write: 0.83 ns (steps: 218)
Size (bytes): 16384, Stride (bytes): 256, read+write: 0.79 ns (steps: 202)
Size (bytes): 16384, Stride (bytes): 512, read+write: 0.85 ns (steps: 176)
Size (bytes): 16384, Stride (bytes):1024, read+write: 0.71 ns (steps: 170)
Size (bytes): 32768, Stride (bytes): 4, read+write: 0.79 ns (steps: 241)
Size (bytes): 32768, Stride (bytes): 8, read+write: 0.87 ns (steps: 231)
Size (bytes): 32768, Stride (bytes): 16, read+write: 0.88 ns (steps: 228)
Size (bytes): 32768, Stride (bytes): 32, read+write: 0.97 ns (steps: 217)
Size (bytes): 32768, Stride (bytes): 64, read+write: 1.17 ns (steps: 205)
Size (bytes): 32768, Stride (bytes): 128, read+write: 1.00 ns (steps: 210)
Size (bytes): 32768, Stride (bytes): 256, read+write: 0.98 ns (steps: 204)
Size (bytes): 32768, Stride (bytes): 512, read+write: 1.00 ns (steps: 190)
Size (bytes): 32768, Stride (bytes):1024, read+write: 0.95 ns (steps: 168)
Size (bytes): 65536, Stride (bytes): 4, read+write: 0.75 ns (steps: 241)
Size (bytes): 65536, Stride (bytes): 8, read+write: 0.80 ns (steps: 237)
Size (bytes): 65536, Stride (bytes): 16, read+write: 0.93 ns (steps: 226)
Size (bytes): 65536, Stride (bytes): 32, read+write: 1.01 ns (steps: 218)
Size (bytes): 65536, Stride (bytes): 64, read+write: 1.51 ns (steps: 179)
Size (bytes): 65536, Stride (bytes): 128, read+write: 1.49 ns (steps: 181)
Size (bytes): 65536, Stride (bytes): 256, read+write: 1.41 ns (steps: 177)
Size (bytes): 65536, Stride (bytes): 512, read+write: 1.42 ns (steps: 176)
Size (bytes): 65536, Stride (bytes):1024, read+write: 1.54 ns (steps: 156)
Size (bytes): 131072, Stride (bytes): 4, read+write: 0.76 ns (steps: 238)
Size (bytes): 131072, Stride (bytes): 8, read+write: 0.87 ns (steps: 229)
Size (bytes): 131072, Stride (bytes): 16, read+write: 0.96 ns (steps: 219)
```

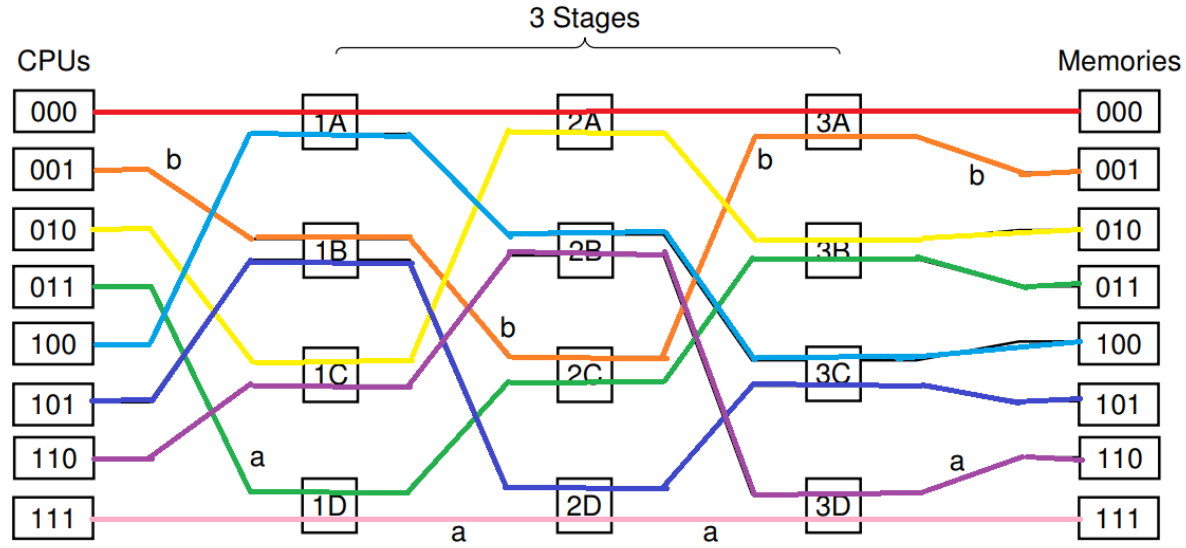
Size (bytes): 131072, Stride (bytes): 32, read+write: 0.99 ns (steps: 212)
Size (bytes): 131072, Stride (bytes): 64, read+write: 1.53 ns (steps: 177)
Size (bytes): 131072, Stride (bytes): 128, read+write: 1.56 ns (steps: 173)
Size (bytes): 131072, Stride (bytes): 256, read+write: 1.50 ns (steps: 173)
Size (bytes): 131072, Stride (bytes): 512, read+write: 1.47 ns (steps: 177)
Size (bytes): 131072, Stride (bytes):1024, read+write: 1.65 ns (steps: 158)
Size (bytes): 262144, Stride (bytes): 4, read+write: 0.86 ns (steps: 232)
Size (bytes): 262144, Stride (bytes): 8, read+write: 0.87 ns (steps: 229)
Size (bytes): 262144, Stride (bytes): 16, read+write: 1.06 ns (steps: 208)
Size (bytes): 262144, Stride (bytes): 32, read+write: 1.41 ns (steps: 184)
Size (bytes): 262144, Stride (bytes): 64, read+write: 2.26 ns (steps: 137)
Size (bytes): 262144, Stride (bytes): 128, read+write: 2.46 ns (steps: 130)
Size (bytes): 262144, Stride (bytes): 256, read+write: 2.31 ns (steps: 134)
Size (bytes): 262144, Stride (bytes): 512, read+write: 2.41 ns (steps: 133)
Size (bytes): 262144, Stride (bytes):1024, read+write: 2.68 ns (steps: 123)
Size (bytes): 524288, Stride (bytes): 4, read+write: 0.82 ns (steps: 231)
Size (bytes): 524288, Stride (bytes): 8, read+write: 0.84 ns (steps: 227)
Size (bytes): 524288, Stride (bytes): 16, read+write: 0.95 ns (steps: 220)
Size (bytes): 524288, Stride (bytes): 32, read+write: 1.56 ns (steps: 173)
Size (bytes): 524288, Stride (bytes): 64, read+write: 3.13 ns (steps: 115)
Size (bytes): 524288, Stride (bytes): 128, read+write: 3.36 ns (steps: 107)
Size (bytes): 524288, Stride (bytes): 256, read+write: 4.00 ns (steps: 95)
Size (bytes): 524288, Stride (bytes): 512, read+write: 3.36 ns (steps: 107)
Size (bytes): 524288, Stride (bytes):1024, read+write: 3.60 ns (steps: 100)
Size (bytes): 1048576, Stride (bytes): 4, read+write: 0.95 ns (steps: 220)
Size (bytes): 1048576, Stride (bytes): 8, read+write: 0.89 ns (steps: 224)
Size (bytes): 1048576, Stride (bytes): 16, read+write: 1.03 ns (steps: 213)
Size (bytes): 1048576, Stride (bytes): 32, read+write: 1.47 ns (steps: 177)
Size (bytes): 1048576, Stride (bytes): 64, read+write: 2.75 ns (steps: 120)
Size (bytes): 1048576, Stride (bytes): 128, read+write: 3.56 ns (steps: 104)
Size (bytes): 1048576, Stride (bytes): 256, read+write: 3.70 ns (steps: 100)
Size (bytes): 1048576, Stride (bytes): 512, read+write: 3.24 ns (steps: 111)
Size (bytes): 1048576, Stride (bytes):1024, read+write: 3.53 ns (steps: 102)
Size (bytes): 2097152, Stride (bytes): 4, read+write: 0.89 ns (steps: 224)
Size (bytes): 2097152, Stride (bytes): 8, read+write: 1.12 ns (steps: 205)
Size (bytes): 2097152, Stride (bytes): 16, read+write: 1.13 ns (steps: 203)
Size (bytes): 2097152, Stride (bytes): 32, read+write: 1.56 ns (steps: 173)
Size (bytes): 2097152, Stride (bytes): 64, read+write: 3.36 ns (steps: 107)
Size (bytes): 2097152, Stride (bytes): 128, read+write: 3.50 ns (steps: 103)
Size (bytes): 2097152, Stride (bytes): 256, read+write: 3.78 ns (steps: 98)
Size (bytes): 2097152, Stride (bytes): 512, read+write: 3.12 ns (steps: 112)
Size (bytes): 2097152, Stride (bytes):1024, read+write: 3.50 ns (steps: 103)
Size (bytes): 4194304, Stride (bytes): 4, read+write: 0.95 ns (steps: 222)
Size (bytes): 4194304, Stride (bytes): 8, read+write: 1.23 ns (steps: 195)
Size (bytes): 4194304, Stride (bytes): 16, read+write: 1.62 ns (steps: 167)
Size (bytes): 4194304, Stride (bytes): 32, read+write: 1.94 ns (steps: 155)
Size (bytes): 4194304, Stride (bytes): 64, read+write: 4.70 ns (steps: 83)
Size (bytes): 4194304, Stride (bytes): 128, read+write: 4.64 ns (steps: 84)
Size (bytes): 4194304, Stride (bytes): 256, read+write: 4.22 ns (steps: 90)
Size (bytes): 4194304, Stride (bytes): 512, read+write: 3.12 ns (steps: 112)

Size (bytes): 4194304, Stride (bytes):1024, read+write: 3.43 ns (steps: 105)
Size (bytes): 8388608, Stride (bytes): 4, read+write: 1.01 ns (steps: 218)
Size (bytes): 8388608, Stride (bytes): 8, read+write: 1.28 ns (steps: 188)
Size (bytes): 8388608, Stride (bytes): 16, read+write: 2.37 ns (steps: 135)
Size (bytes): 8388608, Stride (bytes): 32, read+write: 3.78 ns (steps: 98)
Size (bytes): 8388608, Stride (bytes): 64, read+write: 7.05 ns (steps: 61)
Size (bytes): 8388608, Stride (bytes): 128, read+write: 6.67 ns (steps: 63)
Size (bytes): 8388608, Stride (bytes): 256, read+write: 6.27 ns (steps: 67)
Size (bytes): 8388608, Stride (bytes): 512, read+write: 3.13 ns (steps: 112)
Size (bytes): 8388608, Stride (bytes):1024, read+write: 3.52 ns (steps: 105)
Size (bytes): 16777216, Stride (bytes): 4, read+write: 0.96 ns (steps: 218)
Size (bytes): 16777216, Stride (bytes): 8, read+write: 1.24 ns (steps: 193)
Size (bytes): 16777216, Stride (bytes): 16, read+write: 2.39 ns (steps: 134)
Size (bytes): 16777216, Stride (bytes): 32, read+write: 2.41 ns (steps: 137)
Size (bytes): 16777216, Stride (bytes): 64, read+write: 10.00 ns (steps: 44)
Size (bytes): 16777216, Stride (bytes): 128, read+write: 14.06 ns (steps: 32)
Size (bytes): 16777216, Stride (bytes): 256, read+write: 9.78 ns (steps: 45)
Size (bytes): 16777216, Stride (bytes): 512, read+write: 7.64 ns (steps: 55)
Size (bytes): 16777216, Stride (bytes):1024, read+write: 4.58 ns (steps: 83)
Size (bytes): 33554432, Stride (bytes): 4, read+write: 0.95 ns (steps: 220)
Size (bytes): 33554432, Stride (bytes): 8, read+write: 1.45 ns (steps: 179)
Size (bytes): 33554432, Stride (bytes): 16, read+write: 2.46 ns (steps: 130)
Size (bytes): 33554432, Stride (bytes): 32, read+write: 4.88 ns (steps: 80)
Size (bytes): 33554432, Stride (bytes): 64, read+write: 8.60 ns (steps: 50)
Size (bytes): 33554432, Stride (bytes): 128, read+write: 15.16 ns (steps: 31)
Size (bytes): 33554432, Stride (bytes): 256, read+write: 19.17 ns (steps: 24)
Size (bytes): 33554432, Stride (bytes): 512, read+write: 17.14 ns (steps: 28)
Size (bytes): 33554432, Stride (bytes):1024, read+write: 17.69 ns (steps: 26)
Size (bytes): 67108864, Stride (bytes): 4, read+write: 0.90 ns (steps: 222)
Size (bytes): 67108864, Stride (bytes): 8, read+write: 1.22 ns (steps: 196)
Size (bytes): 67108864, Stride (bytes): 16, read+write: 2.37 ns (steps: 135)
Size (bytes): 67108864, Stride (bytes): 32, read+write: 4.81 ns (steps: 81)
Size (bytes): 67108864, Stride (bytes): 64, read+write: 10.48 ns (steps: 42)
Size (bytes): 67108864, Stride (bytes): 128, read+write: 17.14 ns (steps: 28)
Size (bytes): 67108864, Stride (bytes): 256, read+write: 18.46 ns (steps: 26)
Size (bytes): 67108864, Stride (bytes): 512, read+write: 16.21 ns (steps: 29)
Size (bytes): 67108864, Stride (bytes):1024, read+write: 18.40 ns (steps: 25)
Size (bytes):134217728, Stride (bytes): 4, read+write: 0.92 ns (steps: 218)
Size (bytes):134217728, Stride (bytes): 8, read+write: 1.42 ns (steps: 183)
Size (bytes):134217728, Stride (bytes): 16, read+write: 2.44 ns (steps: 135)
Size (bytes):134217728, Stride (bytes): 32, read+write: 5.13 ns (steps: 78)
Size (bytes):134217728, Stride (bytes): 64, read+write: 10.23 ns (steps: 43)
Size (bytes):134217728, Stride (bytes): 128, read+write: 18.08 ns (steps: 26)
Size (bytes):134217728, Stride (bytes): 256, read+write: 18.80 ns (steps: 25)
Size (bytes):134217728, Stride (bytes): 512, read+write: 17.78 ns (steps: 27)
Size (bytes):134217728, Stride (bytes):1024, read+write: 18.46 ns (steps: 26)

Appendix C - Problem 5 - Q3



Appendix D - Problem 5 - Q5



Appendix E - Problem 5 - Q6