**Homework 2**

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**Problem 1**

According to the problem description, we know that cache block size is 64B, so block offset is 6 bits. Total cache size is 512B, so we can calculate that there are 512B / 64B = 8 blocks. In view of 2-way set associative, the number of sets is 8 / 2 = 4, which can be represented by 2 bits. Note that the address space is 20 bits, therefore, we can use 20-6-2 = 12 bits as a tag.

Trace:

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **Address** | **Tag bits** | **Index bits** | **Block offset bits** | **Result** |
| 0xABCDE | 101010111100 | 11 | 011110 | Miss |
| 0x14327 | 000101000011 | 00 | 100111 | Miss |
| 0xDF148 | 110111110001 | 01 | 001000 | Miss |
| 0x8F220 | 100011110010 | 00 | 100000 | Miss |
| 0xCDE4A | 110011011110 | 01 | 001010 | Miss |
| 0x1432F | 000101000011 | 00 | 101111 | Hit |
| 0x52C22 | 010100101100 | 00 | 100010 | Miss |
| 0xABCF2 | 101010111100 | 11 | 110010 | Hit |
| 0x92DA3 | 100100101101 | 10 | 100011 | Miss |
| 0xF125C | 111100010010 | 01 | 011100 | Miss |

Final cache content:

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| **Set #** | **Way 0** | | | **Way 1** | | |
| **Valid** | **Tag** | **Data** | **Valid** | **Tag** | **Data** |
| 0 | 1 | 000101000011 | 0x14327 | 1 | 010100101100 | 0x52C22 |
| 1 | 1 | 111100010010 | 0xF125C | 1 | 110011011110 | 0xCDE4A |
| 2 | 1 | 100100101101 | 0x92DA3 | 0 | \ | \ |
| 3 | 1 | 101010111100 | 0xABCF2 | 0 | \ | \ |

**Problem 2**

1. AAT = 1 + 0.03\*(15 + 0.3\*300) = 4.15 cycles
2. AAT = 1 + 0.1\*(15 + 0.05\*300) = 4 cycles

**Problem 3**

1. Platform: Linux VM. L1 cache size: 32KB.
2. Experiment screenshot (as a sample):

A screenshot of a cell phone

Description automatically generated

1. The number of elements in the following table is 4096, because I used an uint64 array to test bandwidth, 8B per element. 4096 elements can exactly fill L1 cache.

I stress bandwidth by introducing a command line argument: num\_traversals.

To achieve different access patterns, I apply different array index calculations:

1. Write only:

A close up of a screen

Description automatically generated

So that each access writes to corresponding array location once. No reads included.

1. Read:write = 1:1

A close up of a logo

Description automatically generated

So that each access reads first then update its value.

1. Read:write = 2:1

Screen of a cell phone

Description automatically generated

So that in the inner loop, I read two values, sum them up and write back once.

Usage:

*./bandwidth\_gauger <num\_elements> <num\_traversals>*

Results:

The following table records bandwidth based on different number of traversals and access patterns:

|  |  |  |  |
| --- | --- | --- | --- |
| num\_traversals  access patterns | 100,000 | 1,000,000 | 10,000,000 |
| Write only | 22.865009 GB/s | 23.691270 GB/s | 23.442164 GB/s |
| Read:write = 1:1 | 47.199279 GB/s | 46.871620 GB/s | 46.123013 GB/s |
| Read:write = 2:1 | 88.788531 GB/s | 88.132108 GB/s | 87.767868 GB/s |

Note that I don’t include time in the table, but each testing time is long enough to guarantee stability. For the number of traversals 100,000, 1,000,000 and 10,000,000, their execution time is ~100ms, ~1000ms and ~10000ms respectively.

Discussion:

According to the results, read:write = 2:1 reaches highest bandwidth. As we increase the ratio of reads, the bandwidth increases accordingly. Therefore, I can reasonably speculate this L1 cache has write channels and read channels and more than 1 read channels. Isolating write and read is beneficial to parallelize, hence increase the performance.

1. The largest cache size on my machine is 25344KB. So I can choose the number of elements in my array > 25344KB / 8B = 3244032 🡪 I make it 3,500,000, 7,000,000 and 10,000,000 respectively to see the results. Note that, this time I keep the number of traversals fixed, 10.

|  |  |  |  |
| --- | --- | --- | --- |
| num\_elements  access patterns | 3,500,000 | 7,000,000 | 10,000,000 |
| Write only | 11.847571 GB/s | 10.609930 GB/s | 10.222852 GB/s |
| Read:write = 1:1 | 25.079441 GB/s | 22.189149 GB/s | 22.044579 GB/s |
| Read:write = 2:1 | 35.027063 GB/s | 31.123735 GB/s | 30.892325 GB/s |

Summary:

As I increase the number of elements in the array to surpass the volume the L3 cache, it is apparent that the throughput drops sharply compared to L1 cache’s for all the access patterns. I also observe that, from 3,500,000 to 7,000,000, bandwidth continues decreasing; while further to 10,000,000, it stops.

They do match my expectation because in this case, CPU has to requests from main memory, which is definitely slower than from caches.

**Problem 4**

1. Platform: Linux VM

Mode control (how to run my program)

./matrix <MODE>

If no mode arguments are provided, it will run first 3 modes (see below) one by one. Otherwise, only 4 modes are available:

Mode1: I-J-K;

Mode2: I-K-J;

Mode3: J-K-I;

Mode4: I-J-K with loop tiling

E.g., if you type, *./matrix 1*, it will run I-J-K pattern alone.

1. I-J-K: 1.841612 s

I-K-J: 0.487556 s

J-K-I: 19.799538 s

These results match the note from lecture, but only qualitatively not quantitively. According to the class note, cache misses per inner loop iteration is:

I-J-K: 1.125

I-K-J: 0.25

J-K-I: 2

The statistics means that I-K-J is the better pattern, 4.5 times better than I-J-K and 8 times better than J-K-I, in terms of performance (here, execution time). Therefore, we can clearly see from (b) that the performance ranking matches theory, but the numerical relations don’t. The discrepancy happens on J-K-I, which is practically 40 times worse than I-K-J. One possible reason is that because the locality is compromised, every time CPU fetches next element, it actually needs to request from lower level caches or even from main memory, which increases latency drastically. Another possible can be I am using -O3 optimization, which compiler can take great advantage of locality and can’t do any optimization if no spacious locality can be found, like I-K-J pattern.

1. L2 cache size: 1024KB.

Set such sub-block size as x. Calculate inequation:

3x^2 \* 8 <= 1024KB 🡪 x <= 209

Run my program: *./matrix 4*

1. The tiled version of matrix multiplication runs 1.380306 s, while the normal one runs 1.822339 s.

The block size = 128 (calculation in part (c))

Tiled version is faster I-J-K and J-K-I patterns but still slower than I-K-J.

Discussion:

The tiled version does have performance improvement over plain I-J-K pattern because loop tiling helps improve cache reuse and make vectorization easier. However, I-K-J pattern (with the best use of cache locality) still ranks the first among all versions because spacious locality dominates. Decreasing cache misses can obviously improve performance.