CPU design effects
that can degrade performance of your programs

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- HPC, distributed systems, program optimization

How do we get maximum performance?

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- **Tune to the underlying hardware**

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- We write code for the C++ abstract machine
- Intel CPUs fulfill the contract of this abstract machine
  - But inside they can do whatever they want
- Understanding CPU trade-offs can get us more performance

C++ abstract machine example

```
void foo(int* arr, int count)
{
    for (int i = 0; i < count; i++)
    {
        arr[i]++;
    }
}
```

How fast are the individual array increments?

Hardware effects

- Performance effects caused by a specific CPU/memory implementation

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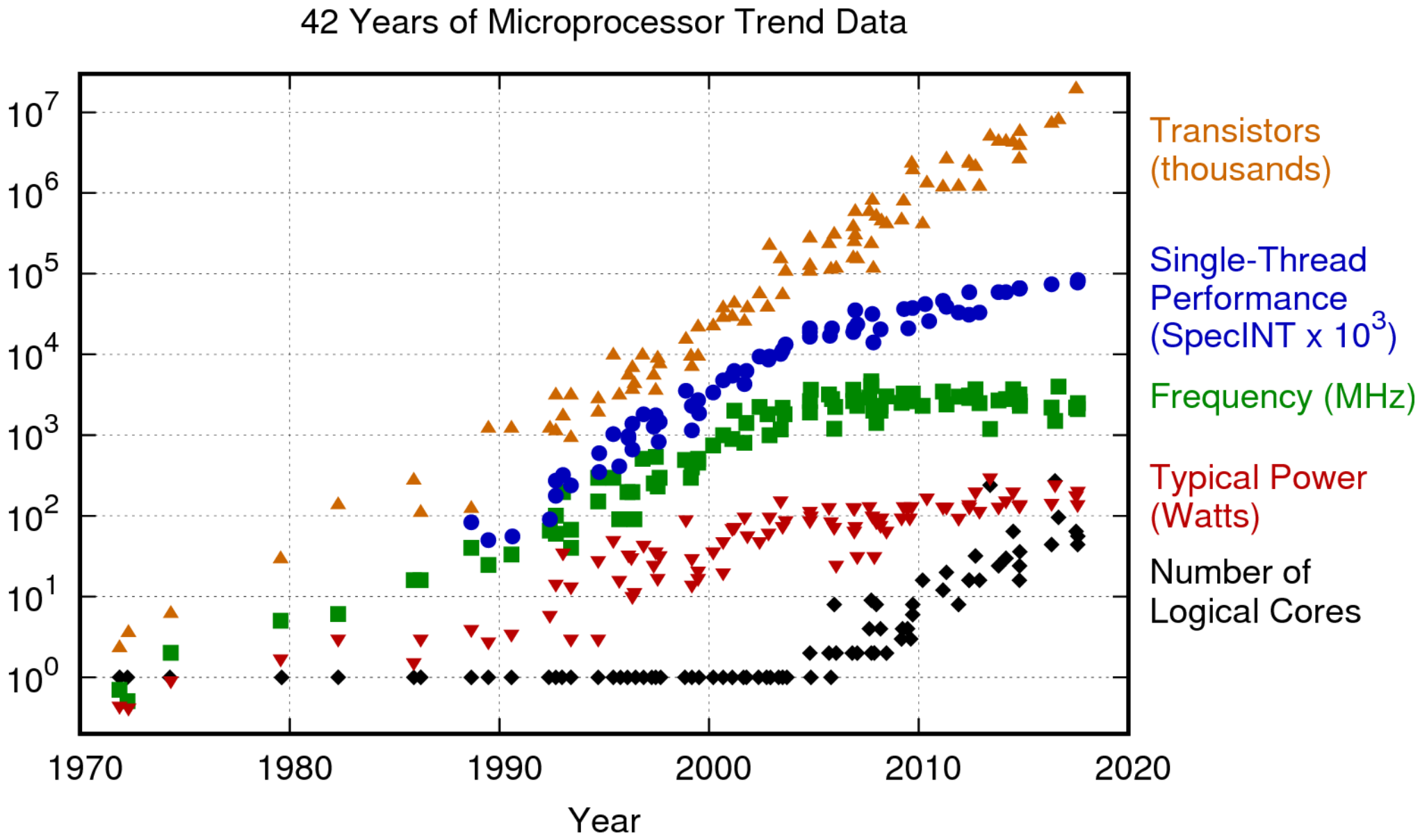
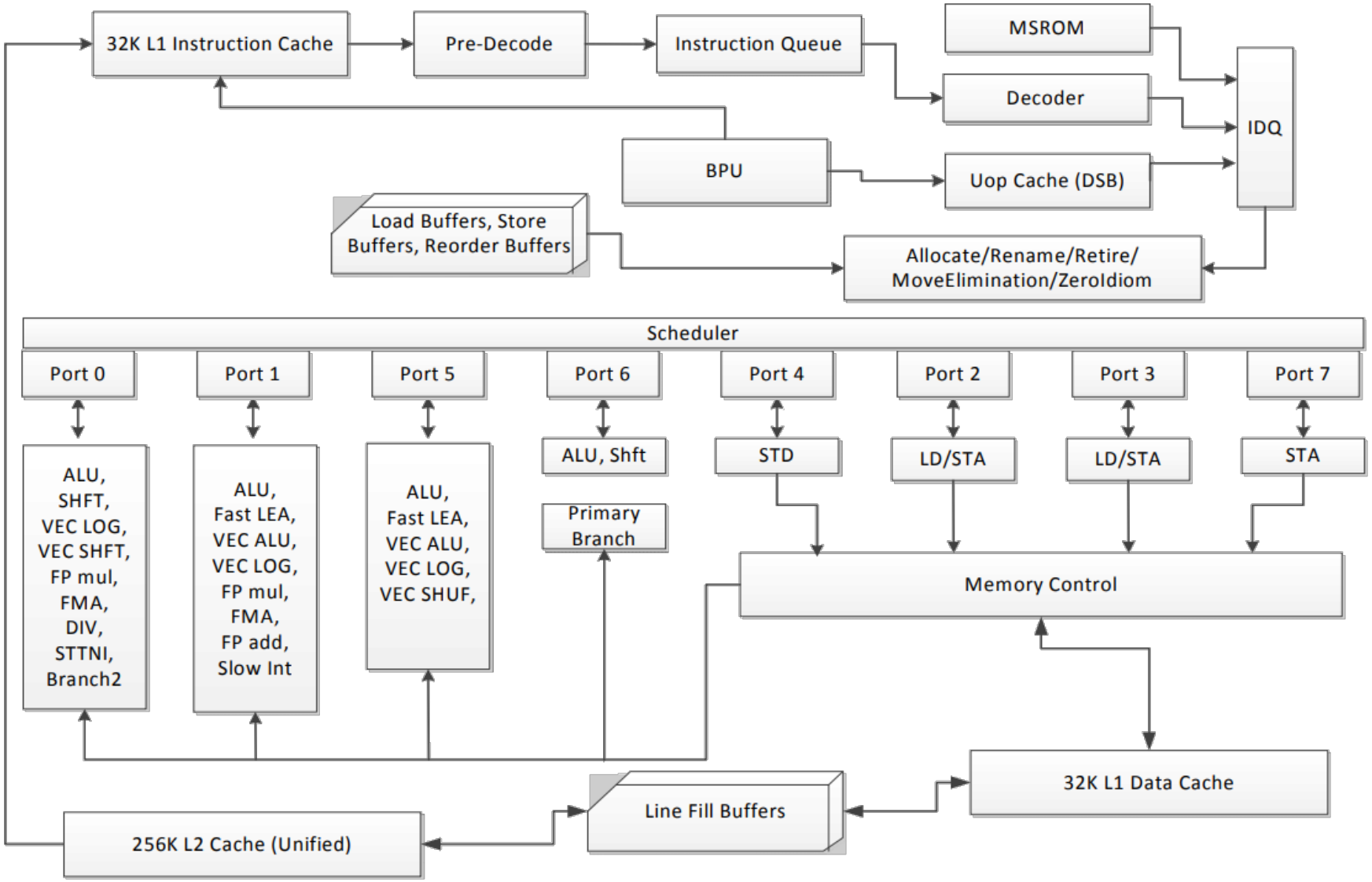
- Performance effects caused by a specific CPU/memory implementation
- Demonstrate some CPU/memory trade-off or assumption
- Impossible to predict from (C++) code alone

Hardware is getting more and more complex



Source: karlrupp.net

Microarchitecture (Haswell)



Source: Intel Architectures Optimization Reference Manual

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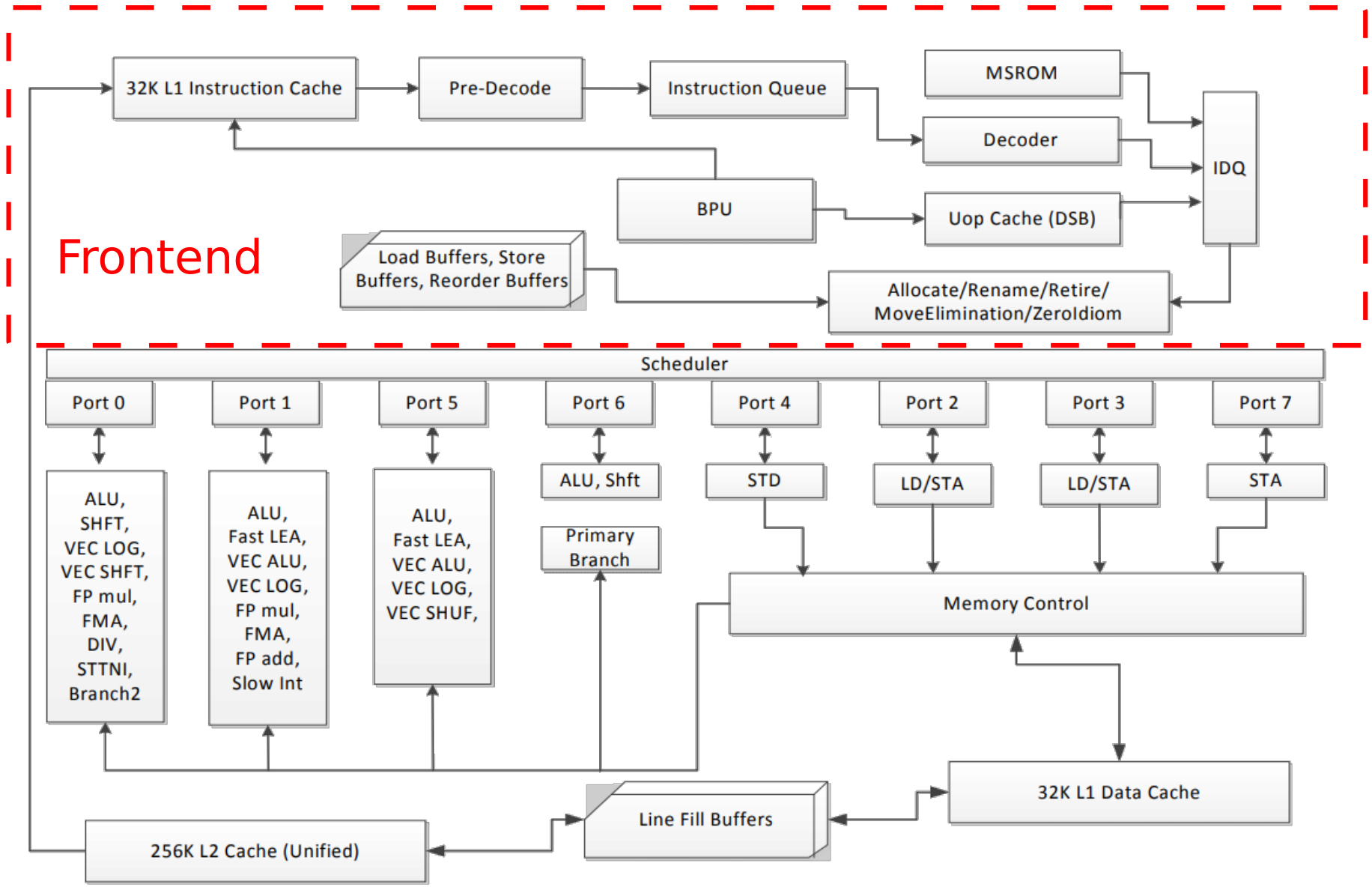

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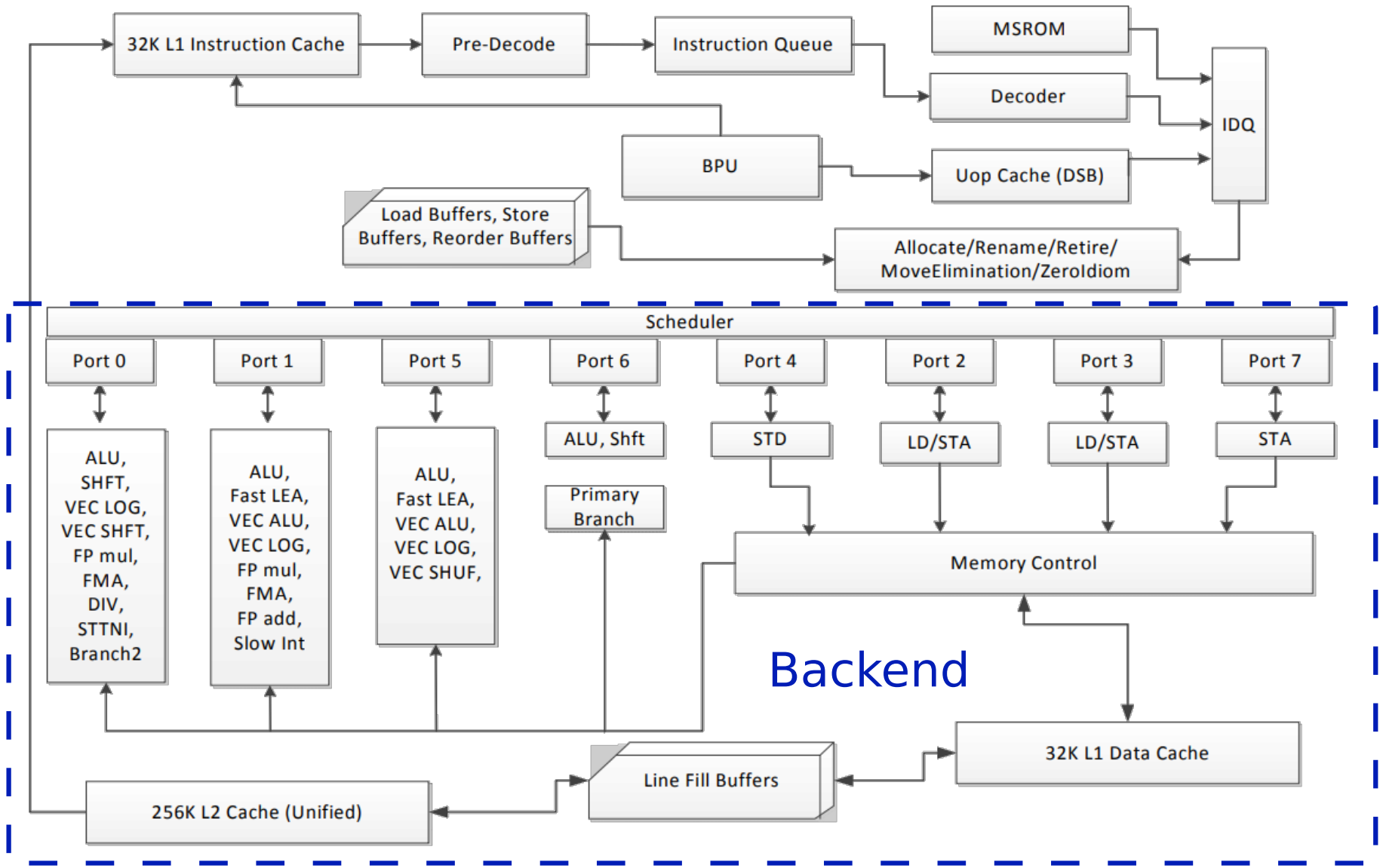

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How bad is it?

- C++ 17 final draft:

http://www.open-std.org/jtc1/sc22/wg21/docs/papers/2017/n4659.pdf
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- Disclaimer #1: Everything will be Intel x86 specific

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- Disclaimer #2: I'm not an expert on this and I may be wrong :-)

Let's see some examples...

Code (backup)

```
std::vector<float> data = /* 32K random floats in [1, 10] */;
float sum = 0;
// std::sort(data.begin(), data.end());
for (auto x : data)
{
    if (x < 6.0f)
    {
        sum += x;
    }
}
```

Result (backup)

```
---------------------------------------------------------------------
Benchmark                           Time             CPU   Iterations
---------------------------------------------------------------------
filter_nosort/32768            133460 ns       132992 ns         5284
filter_sorted/32768             63069 ns        62991 ns        12547
```

Most upvoted Stack Overflow question

Why is it faster to process a sorted array than an unsorted array?

22447

10294

Here is a piece of C++ code that seems very peculiar. For some strange reason, sorting the data miraculously makes the code almost six times faster.

```
#include <algorithm>
#include <ctime>
#include <iostream>

int main()
{
    // Generate data
    const unsigned arraySize = 32768;
    int data[arraySize];

    for (unsigned c = 0; c < arraySize; ++c)
        data[c] = std::rand() % 256;

    // !!! With this, the next loop runs faster
    std::sort(data, data + arraySize);

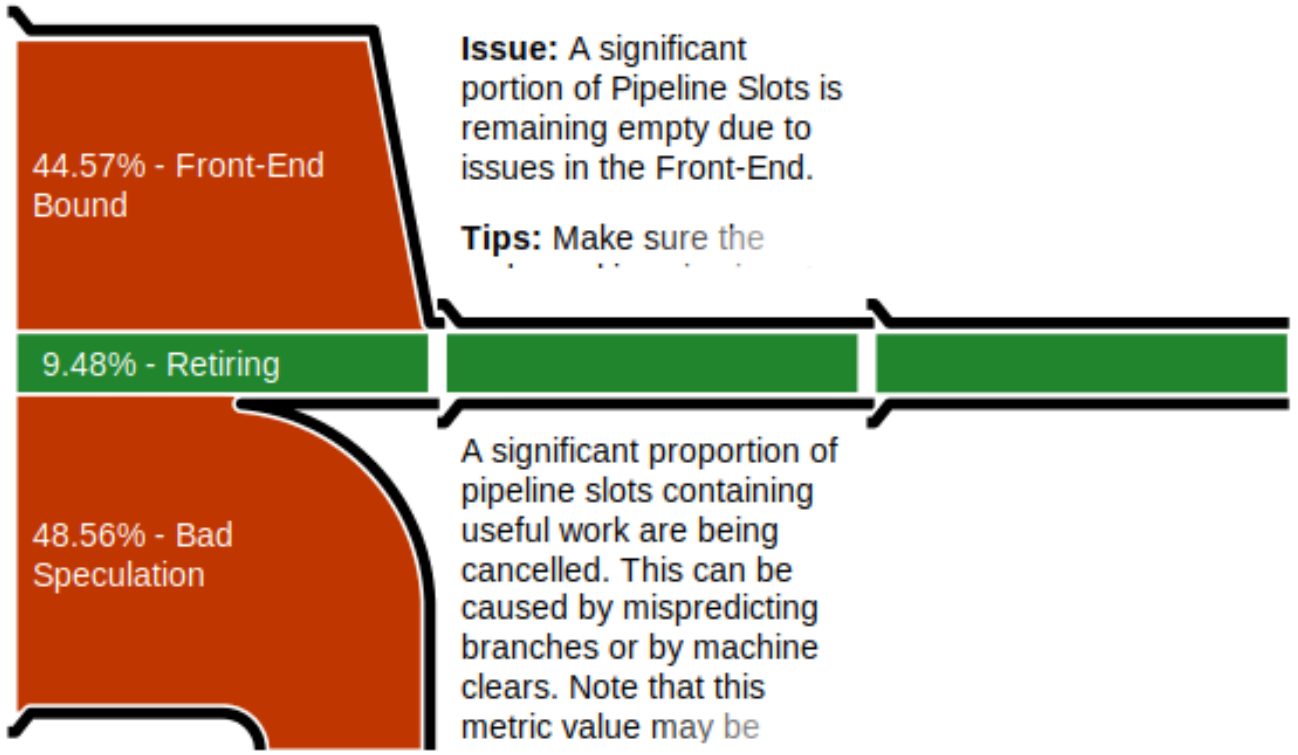
    // Test
    clock_t start = clock();
    long long sum = 0;

    for (unsigned i = 0; i < 100000; ++i)
    {
        // Primary loop
        for (unsigned c = 0; c < arraySize; ++c)
        {
            if (data[c] >= 128)
                sum += data[c];
        }
```

What is going on? (Intel Amplifier - VTune)

Elapsed Time: 2.222s

Clockticks:	6,736,800,000	
Instructions Retired:	2,942,800,000	
CPI Rate:	2.289	
MUX Reliability:	0.802	
Retiring:	9.5%	of Pipeline Slots
Front-End Bound:	44.6%	of Pipeline Slots
Front-End Latency:	31.1%	of Pipeline Slots
ICache Misses:	0.0%	of Clockticks
ITLB Overhead:	0.2%	of Clockticks
Branch Resteers:	13.4%	of Clockticks
Mispredicts Resteers:	12.6%	of Clockticks
Clears Resteers:	0.0%	of Clockticks
Unknown Branches:	0.8%	of Clockticks
DSB Switches:	0.0%	of Clockticks
Length Changing Prefixes:	0.0%	of Clockticks
MS Switches:	4.5%	of Clockticks
Front-End Bandwidth:	13.5%	of Pipeline Slots
Bad Speculation:	48.6%	of Pipeline Slots
Branch Mispredict:	48.6%	of Pipeline Slots
Machine Clears:	0.0%	of Pipeline Slots
Back-End Bound:	0.0%	of Pipeline Slots
Total Thread Count:	1	
Paused Time:	0s	



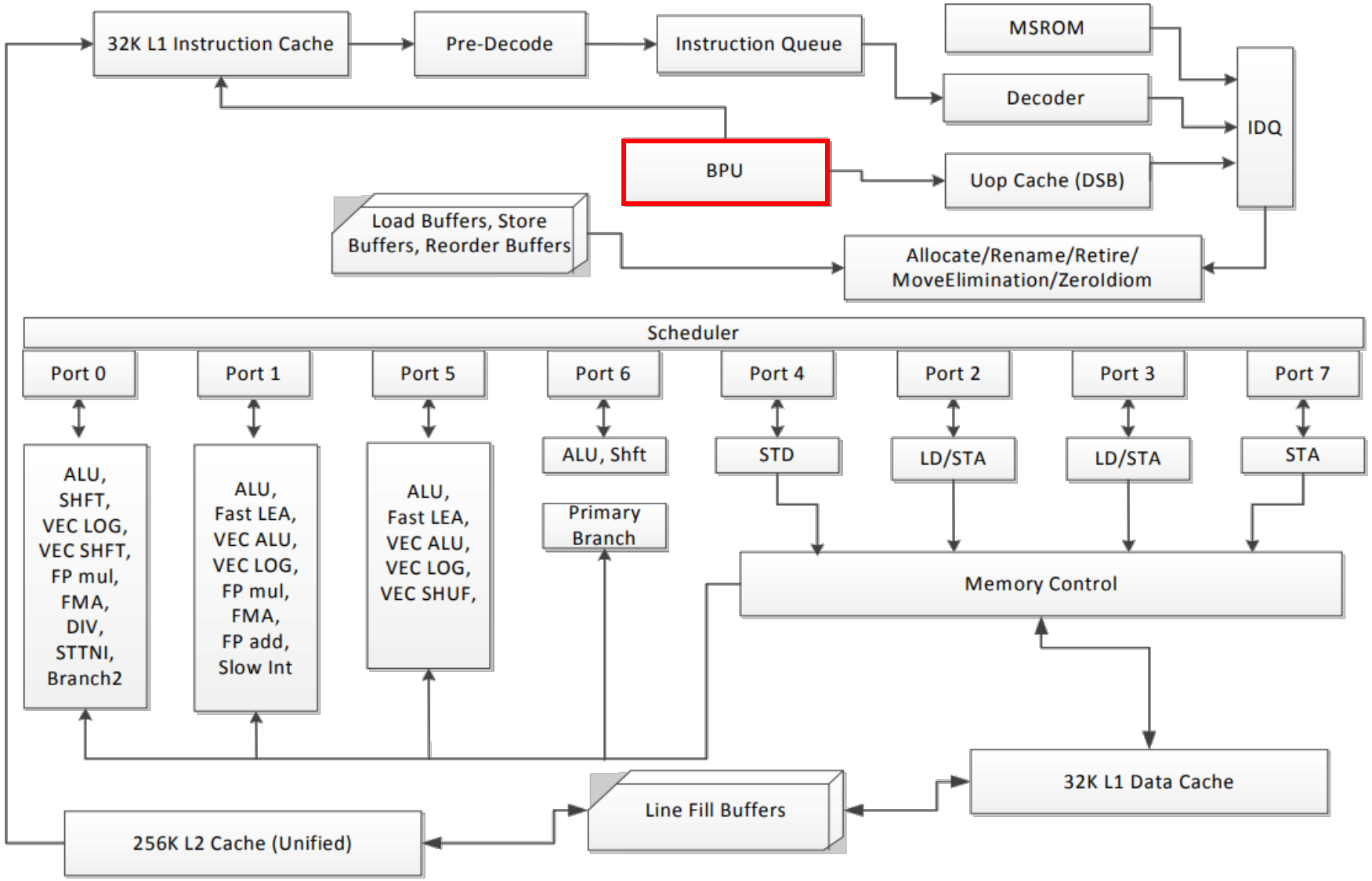
µPipe

This diagram represents inefficiencies in CPU usage. Treat it as a pipe with an output flow equal to the "pipe efficiency" ratio: (Actual Instructions Retired)/(Maximum Possible Instruction Retired). If there are pipeline stalls decreasing the pipe efficiency, the pipe shape gets more narrow.

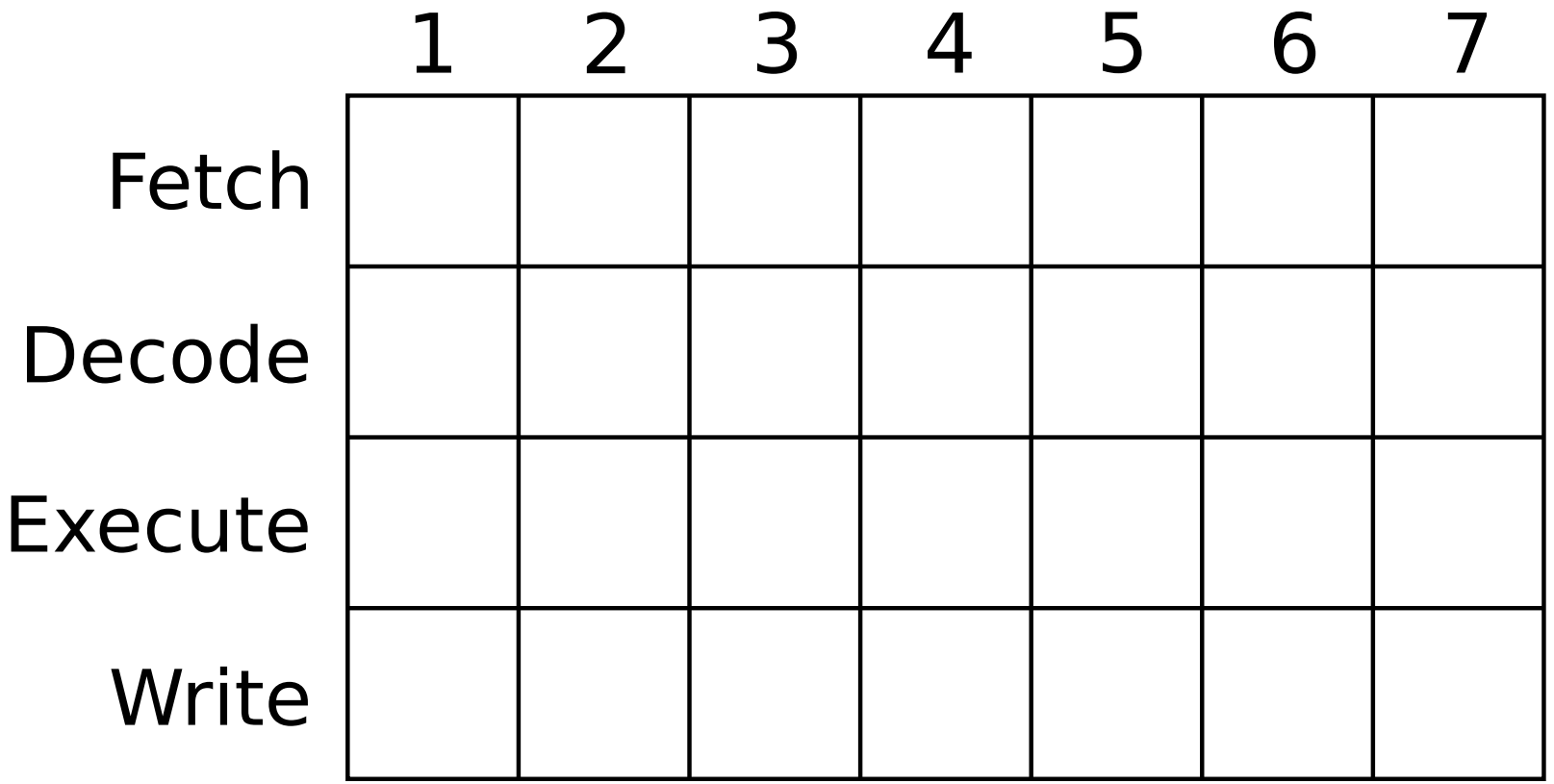
What is going on? (perf)

```
$ perf stat ./example0a --benchmark_filter=nosort
    853,672012  task-clock (msec) #   0,997 CPUs utilized
            30  context-switches  #   0,035 K/sec
             0  cpu-migrations    #   0,000 K/sec
           199  page-faults       #   0,233 K/sec
 3 159 530 915  cycles            #   3,701 GHz
 1 475 799 619  instructions      #   0,47  insn per cycle
   419 608 357  branches          # 491,533 M/sec
   102 425 035  branch-misses     #  24,41% of all branches
```

Branch predictor



CPU pipeline 101

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7   xor rax,rdx
8   add rax,rcx
9   cmp rax,rbx
10  je 15
11  inc rcx
⋮
15  ret
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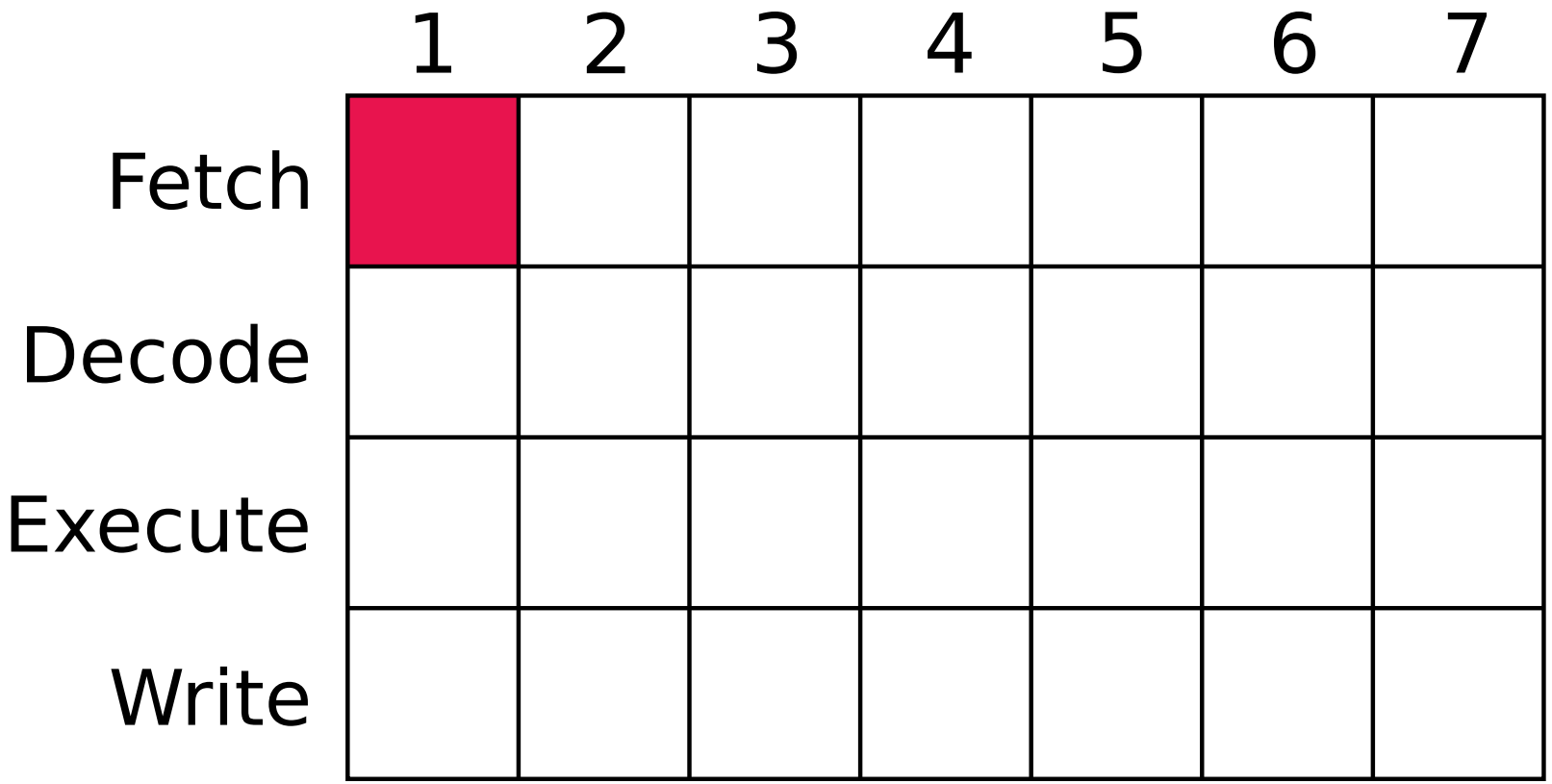


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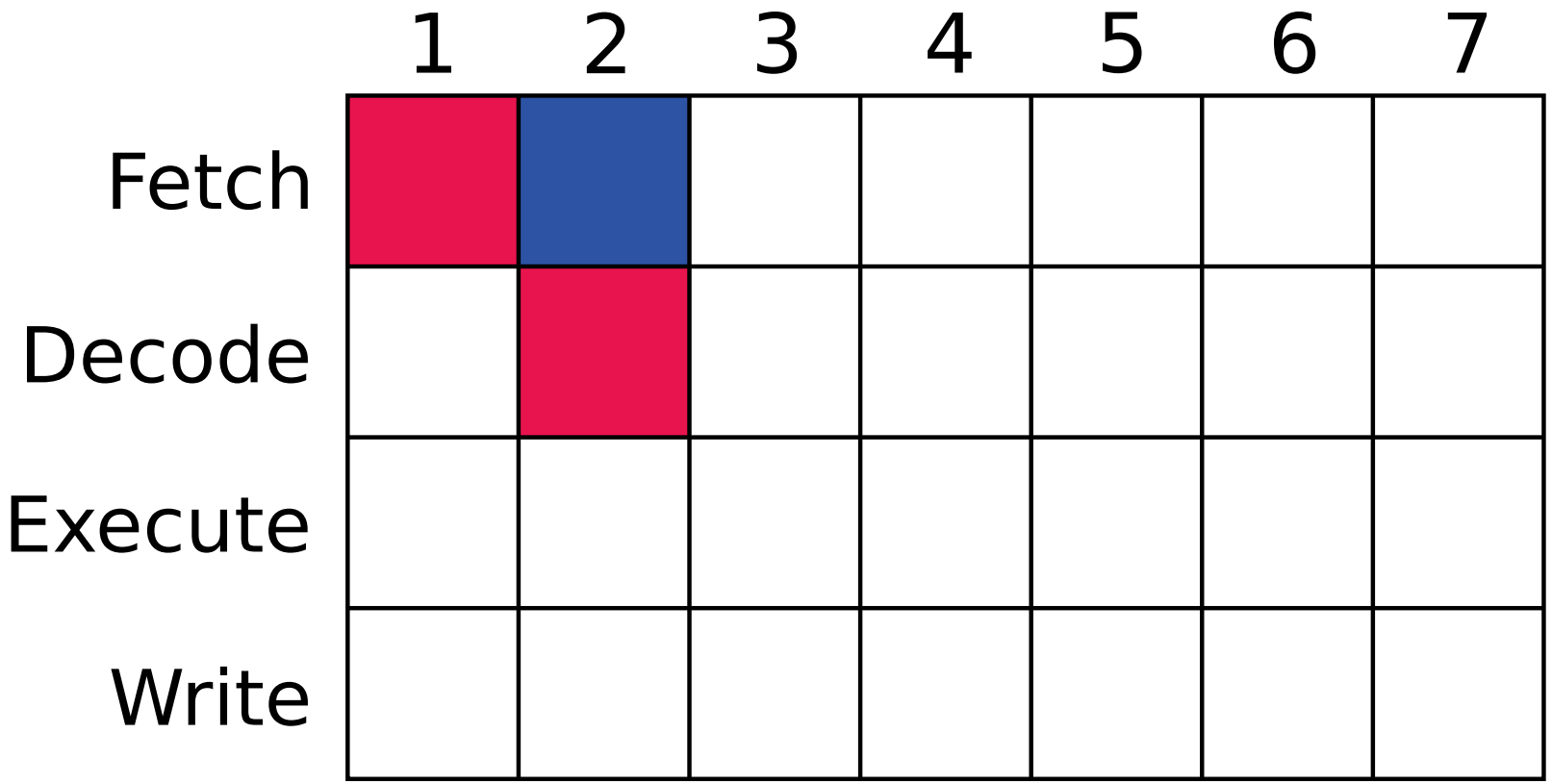


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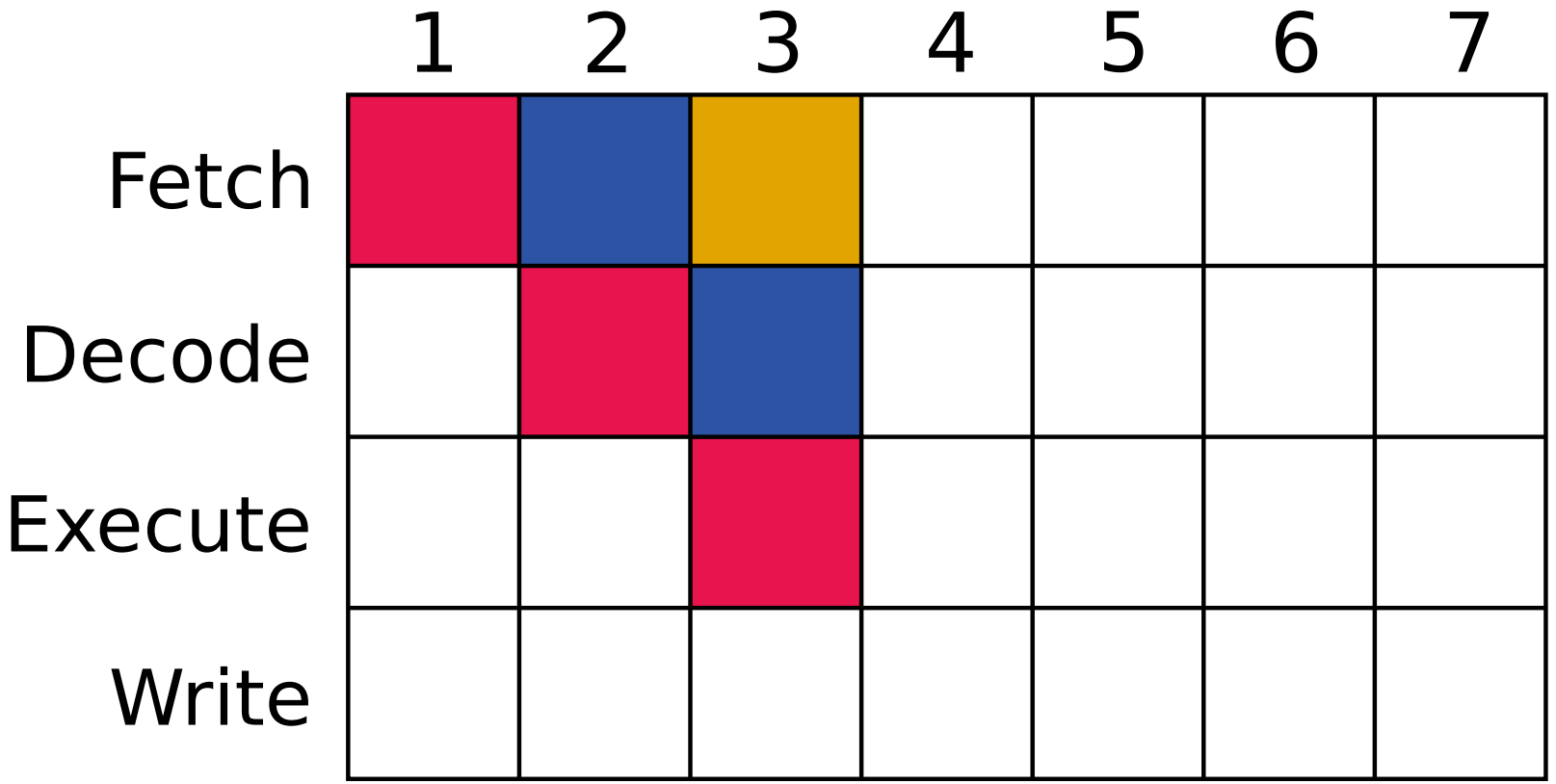


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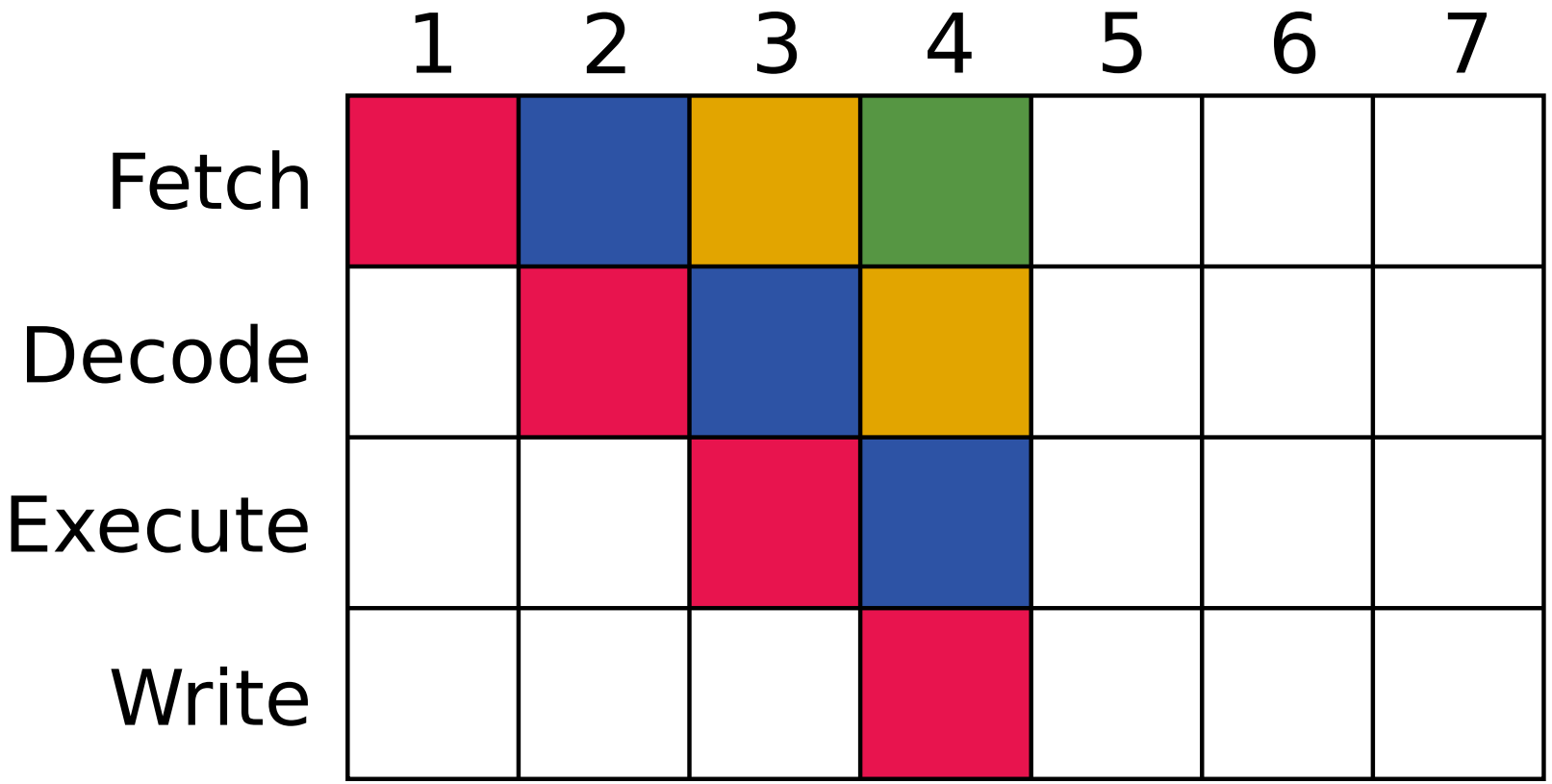


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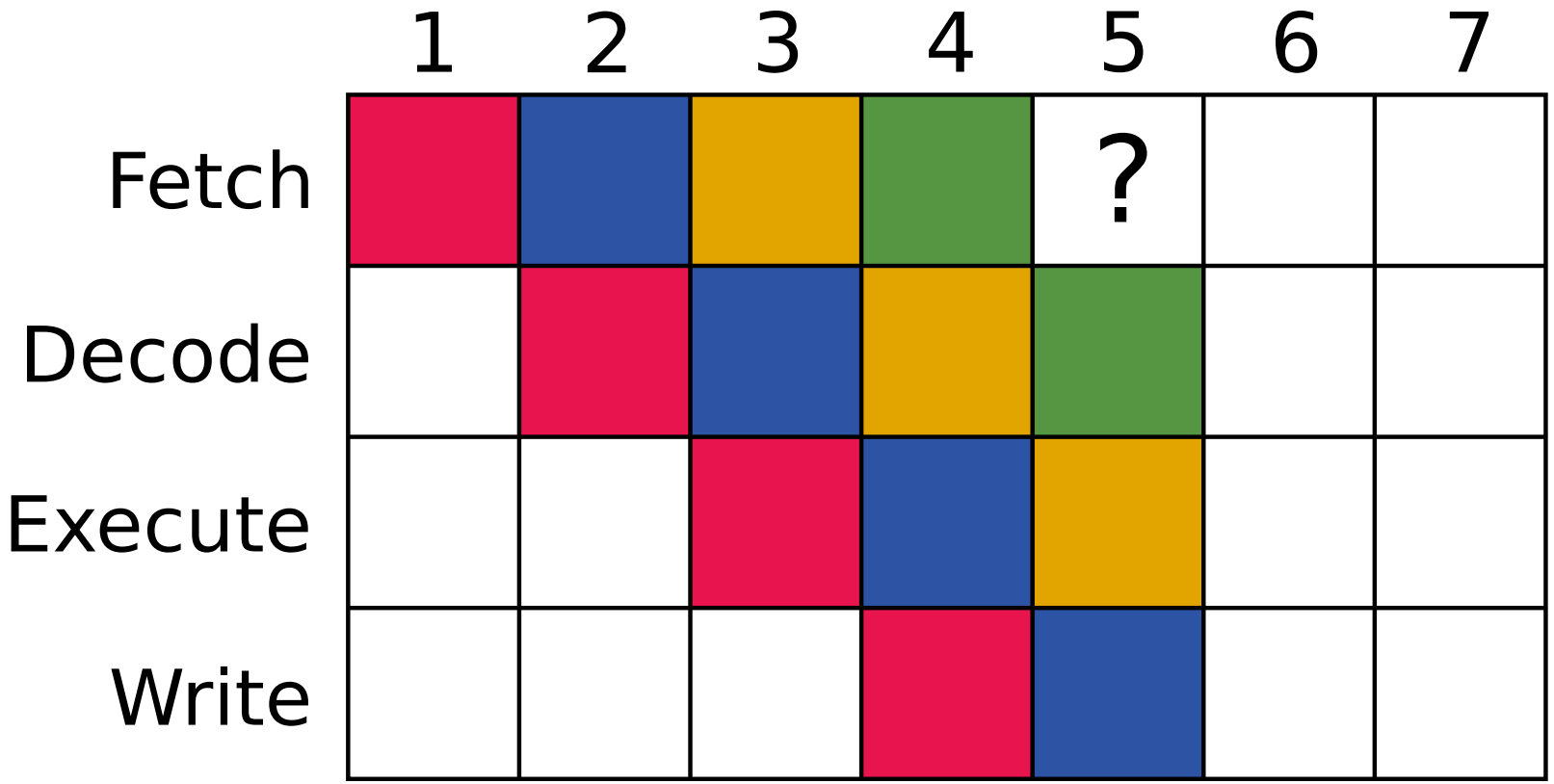


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Branch predictor

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Branch predictor

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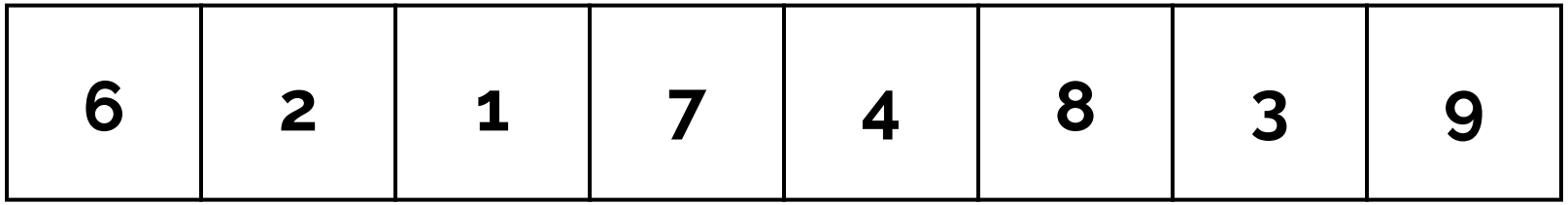
- Misprediction can cost ~15-20 cycles!

Simple branch predictor - unsorted array

```
if (data[i] < 6) {
    ...
}
```



Prediction: Not taken

Simple branch predictor - unsorted array

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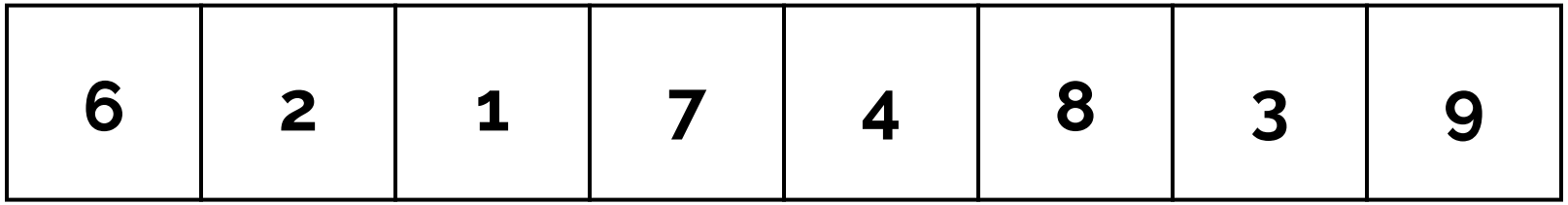

6 < 6?

Prediction: Not taken

Simple branch predictor - unsorted array

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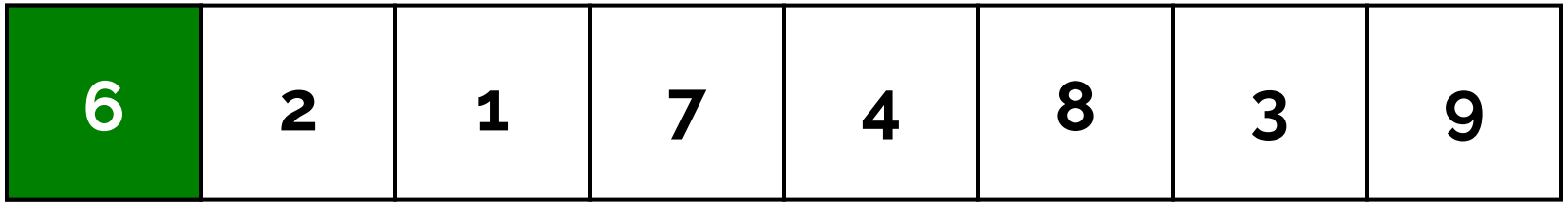
    ...
}
```



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Prediction: Not taken

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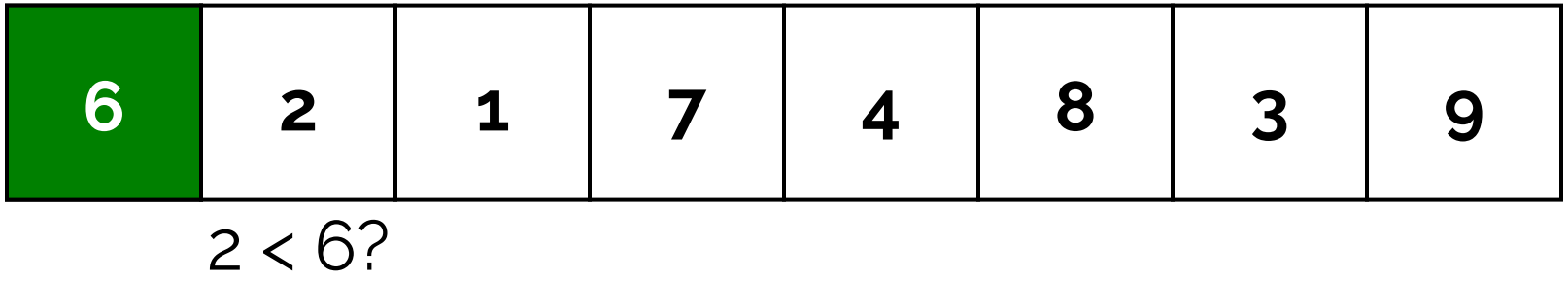

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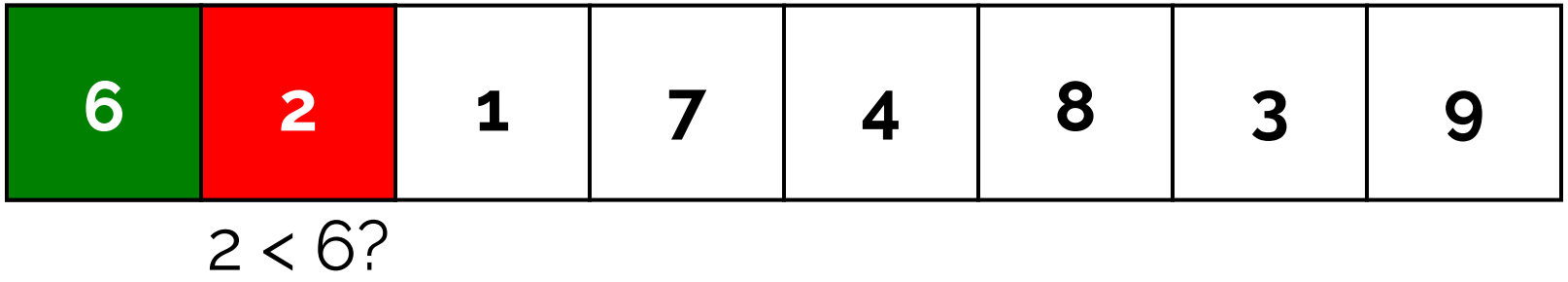

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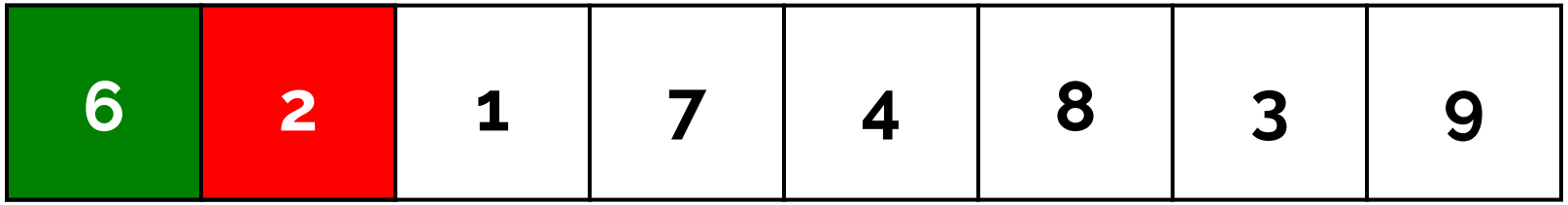

1 < 6?

Prediction: Taken

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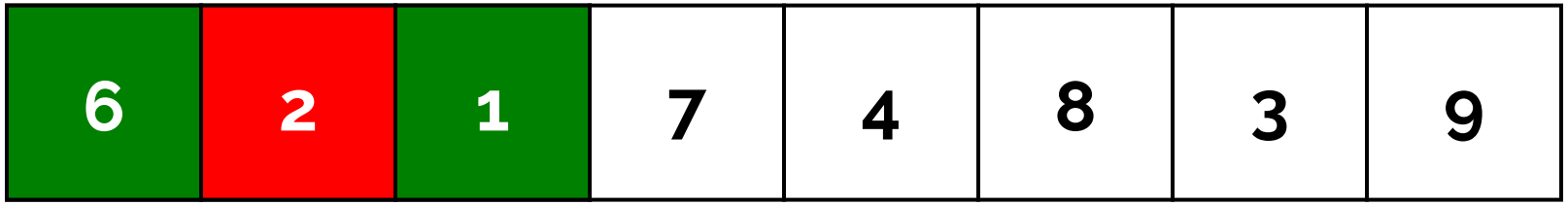
    ...
}
```



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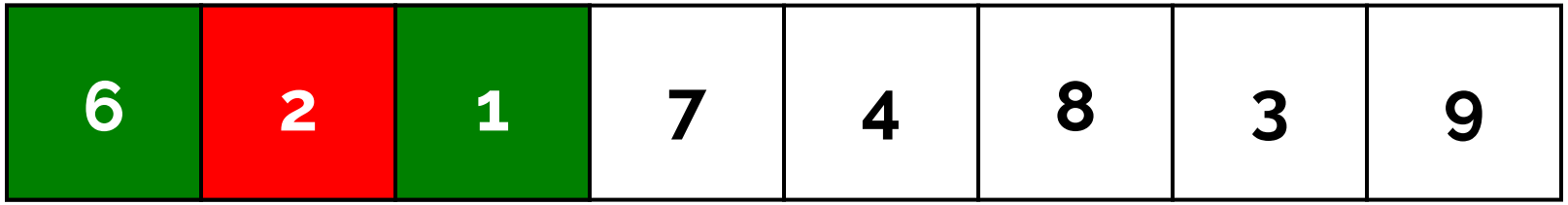

7 < 6?

Prediction: Taken

Simple branch predictor - unsorted array

```
if (data[i] < 6) {
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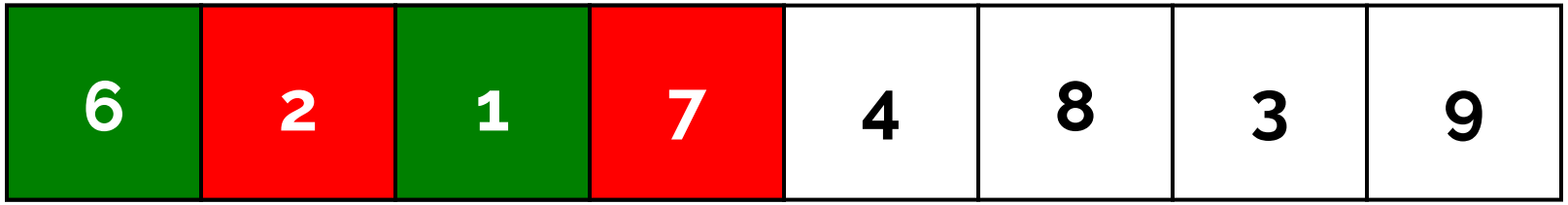
```



7 < 6?

Prediction: Not taken

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if (data[i] < 6) {
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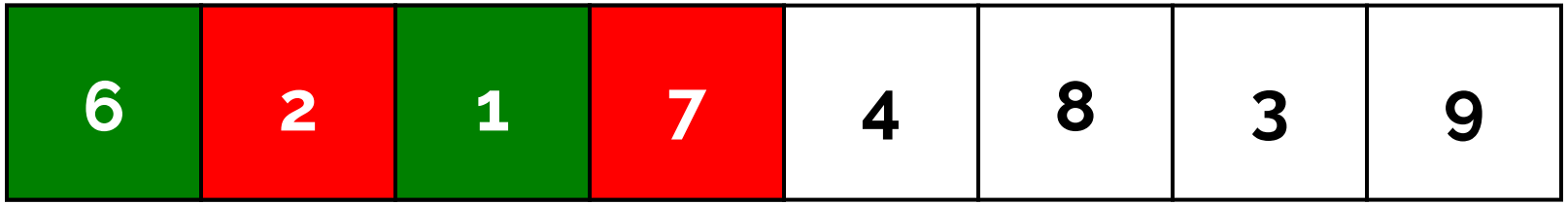

4 < 6?

Prediction: Not taken

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if (data[i] < 6) {
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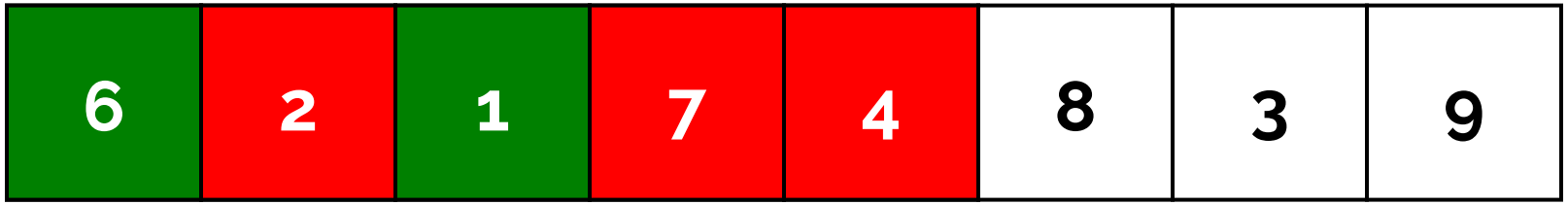
}
```



4 < 6?

Prediction: Taken

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if (data[i] < 6) {
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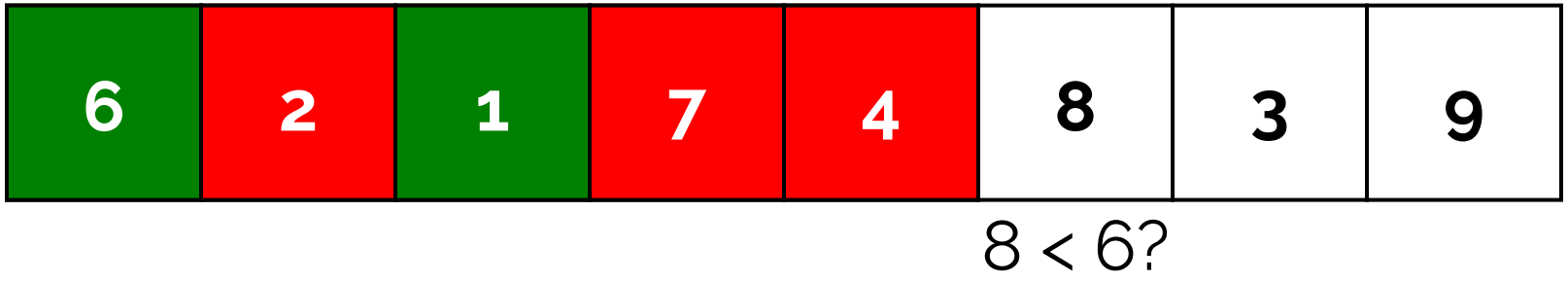
}
```



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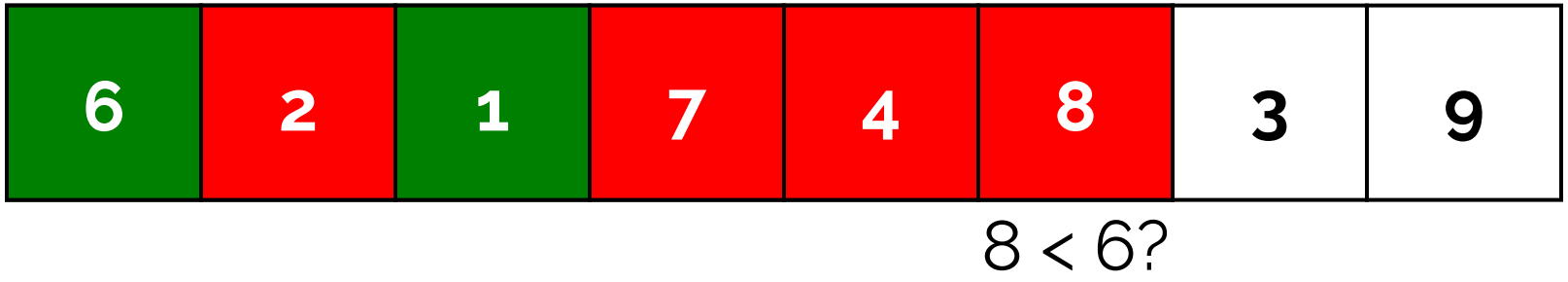

Prediction: Not taken

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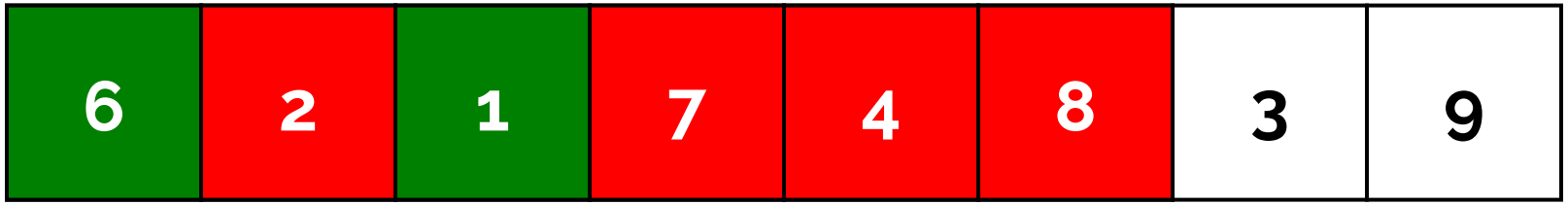

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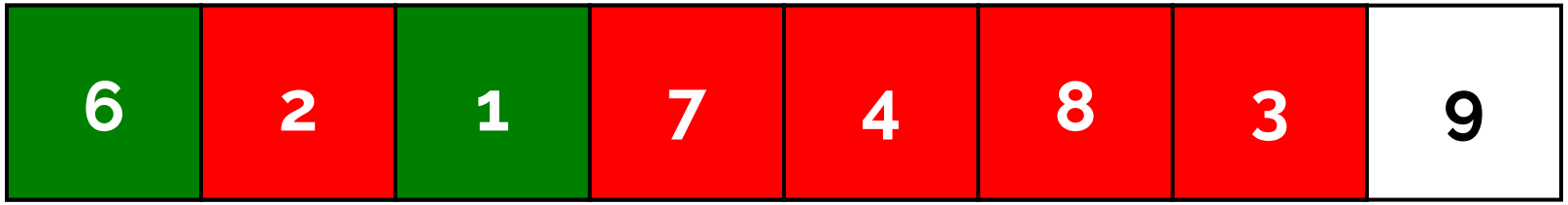

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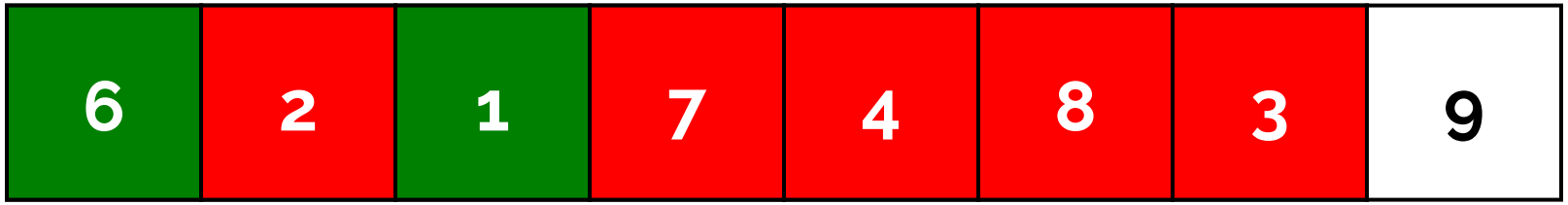

9 < 6?

Prediction: Taken

Simple branch predictor - unsorted array

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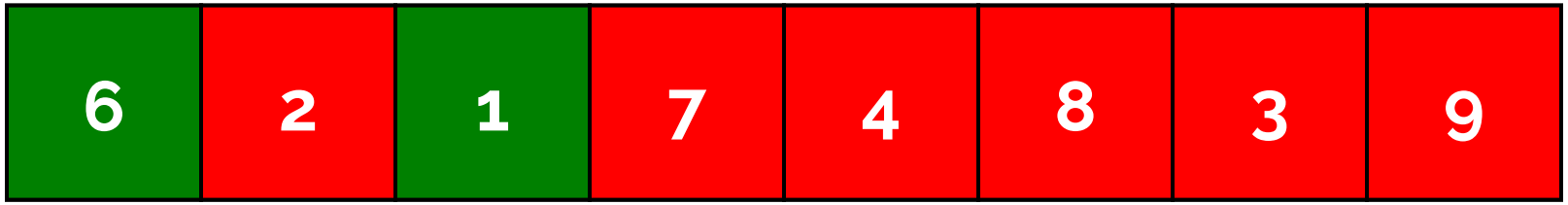

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Simple branch predictor - unsorted array

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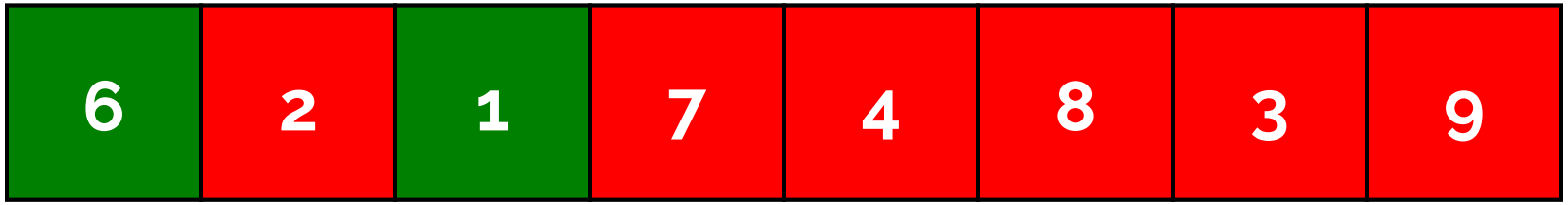

Prediction: Not taken

2 hits, 6 misses (25% hit rate)

Simple branch predictor - sorted array

```
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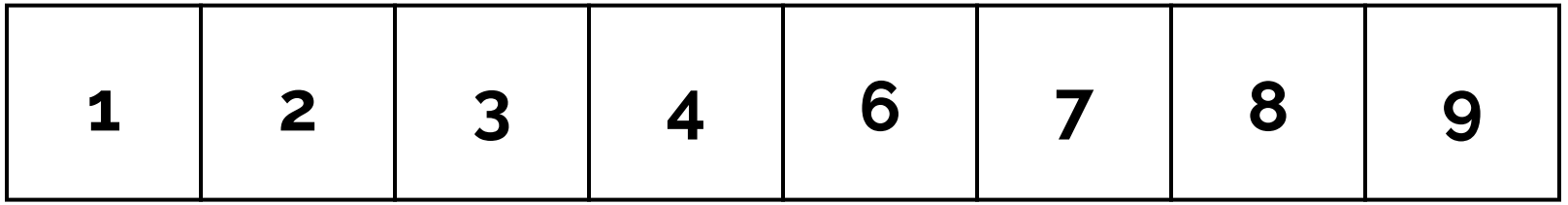

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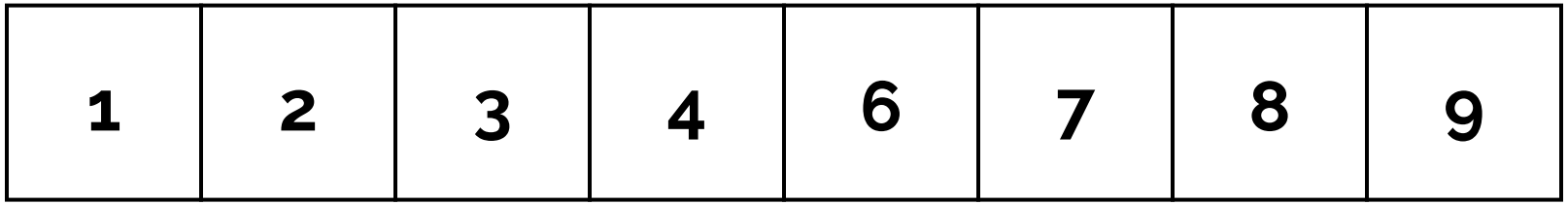
}
```

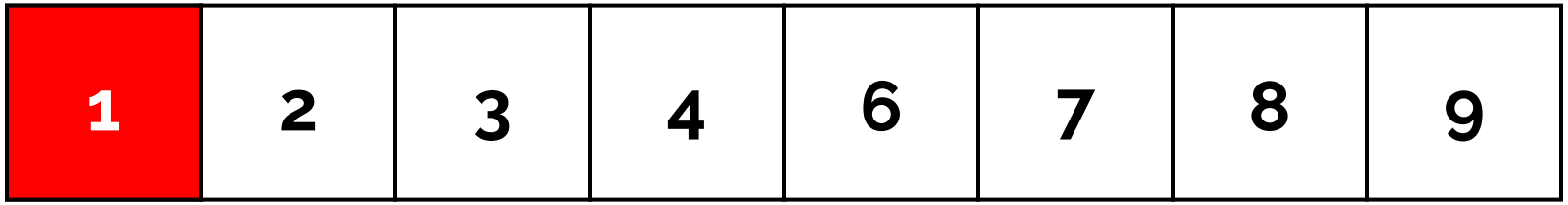


1 < 6?

Prediction: Not taken

Simple branch predictor - sorted array

```
if (data[i] < 6) {
    ...
}
```



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```
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    ...
}
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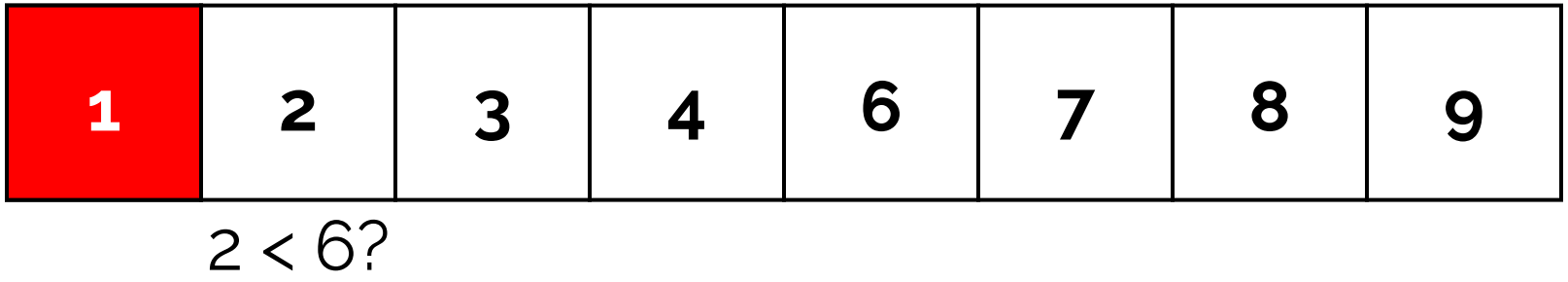
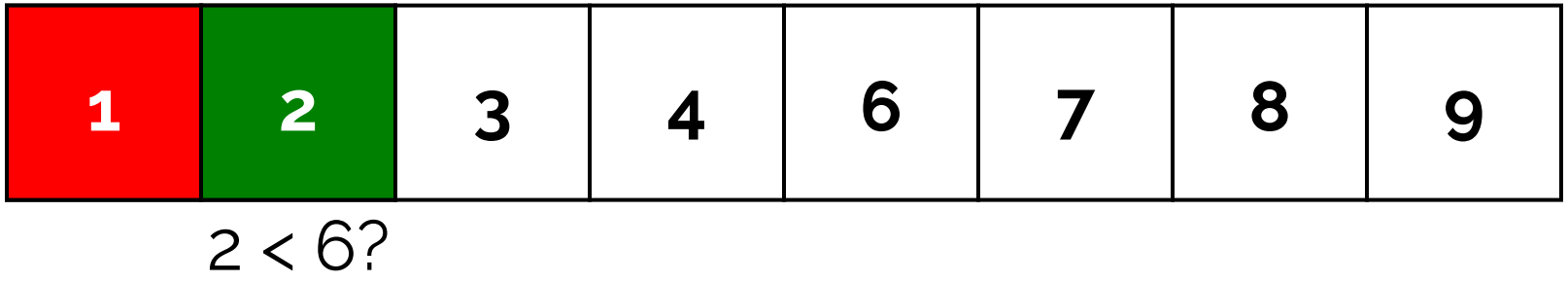


Prediction: Taken

Simple branch predictor - sorted array

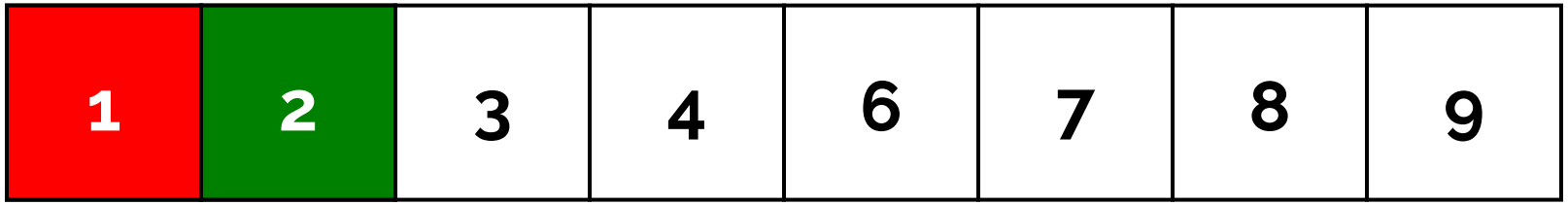
```
if (data[i] < 6) {
    ...
}
```



Prediction: Taken

Simple branch predictor - sorted array

```
if (data[i] < 6) {
    ...
}
```

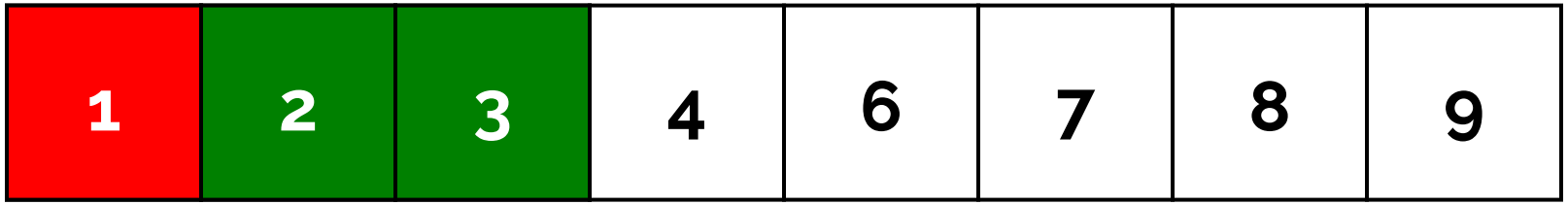


3 < 6?

Prediction: Taken

Simple branch predictor - sorted array

```
if (data[i] < 6) {
    ...
}
```

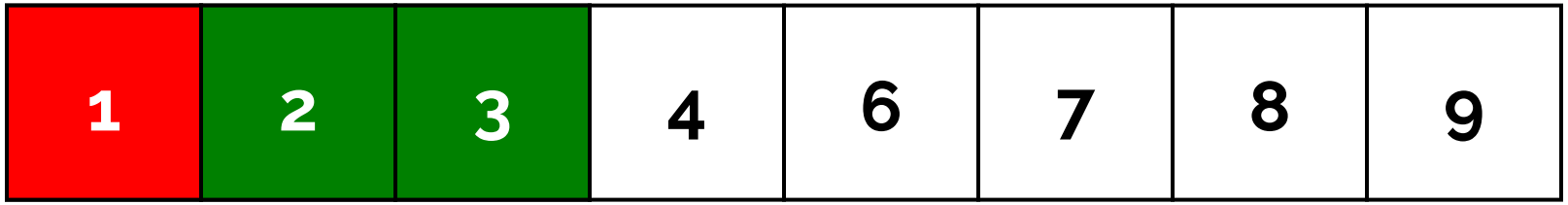


3 < 6?

Prediction: Taken

Simple branch predictor - sorted array

```
if (data[i] < 6) {
    ...
}
```

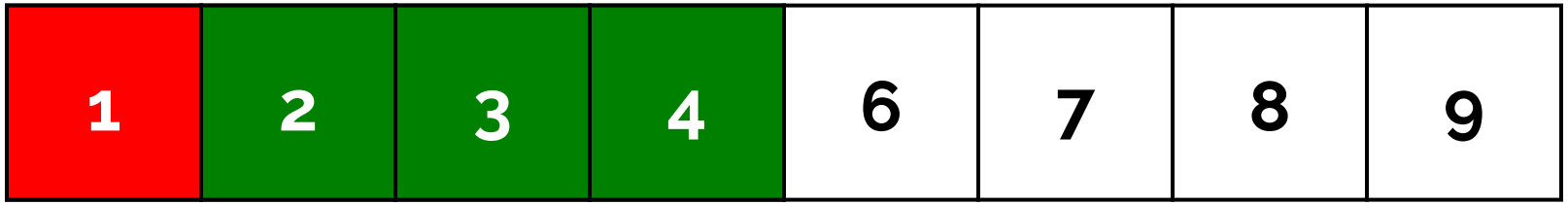


4 < 6?

Prediction: Taken

Simple branch predictor - sorted array

```
if (data[i] < 6) {
    ...
}
```

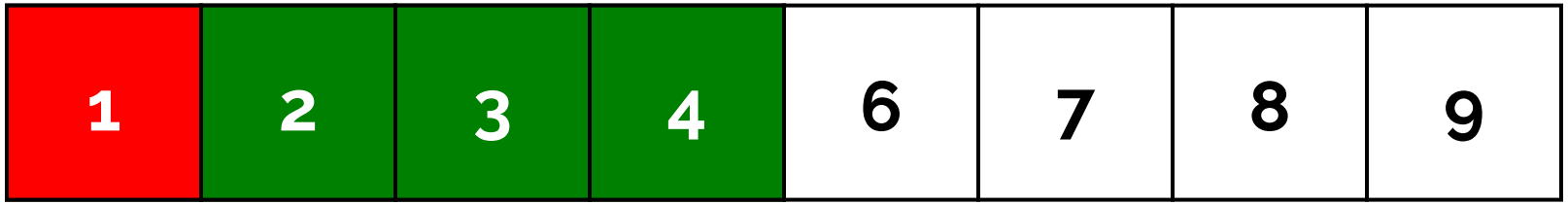


4 < 6?

Prediction: Taken

Simple branch predictor - sorted array

```
if (data[i] < 6) {
    ...
}
```

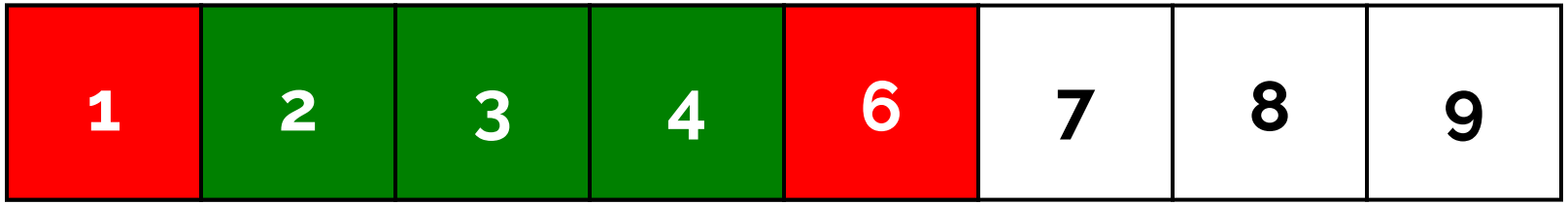


6 < 6?

Prediction: Taken

Simple branch predictor - sorted array

```
if (data[i] < 6) {
    ...
}
```

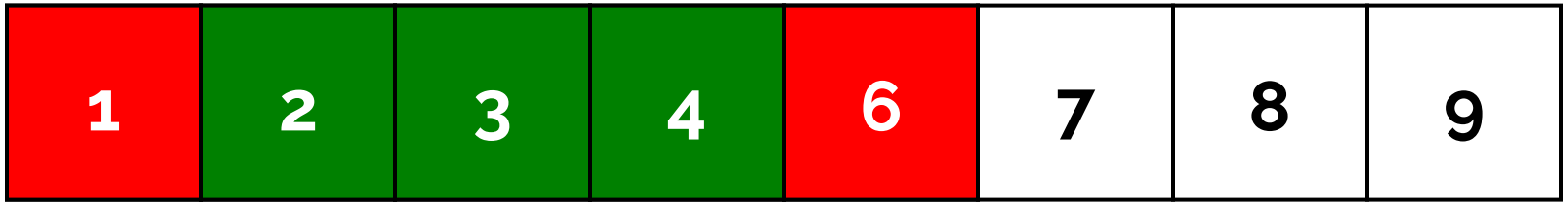


6 < 6?

Prediction: Not taken

Simple branch predictor - sorted array

```
if (data[i] < 6) {
    ...
}
```

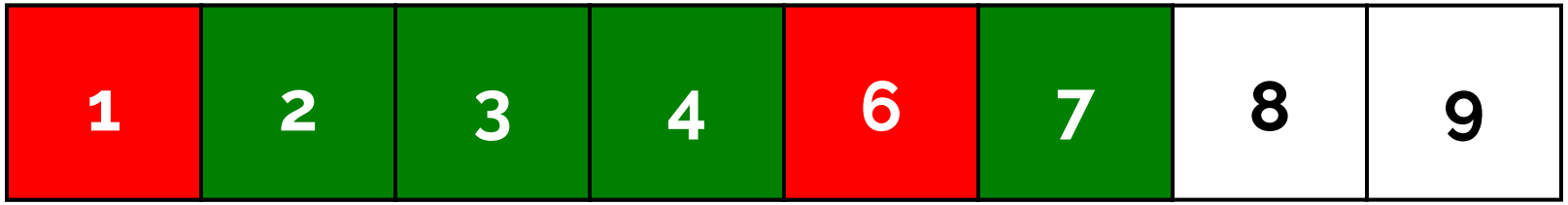


7 < 6?

Prediction: Not taken

Simple branch predictor - sorted array

```
if (data[i] < 6) {
    ...
}
```

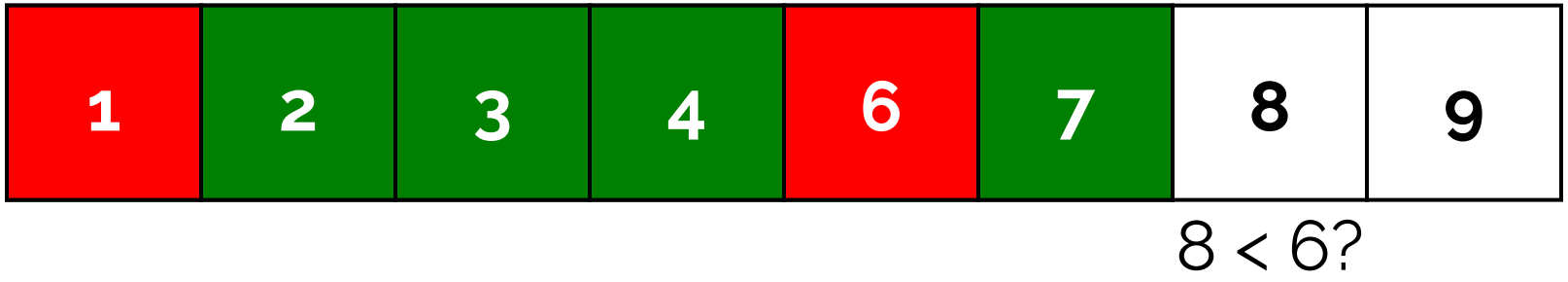


7 < 6?

Prediction: Not taken

Simple branch predictor - sorted array

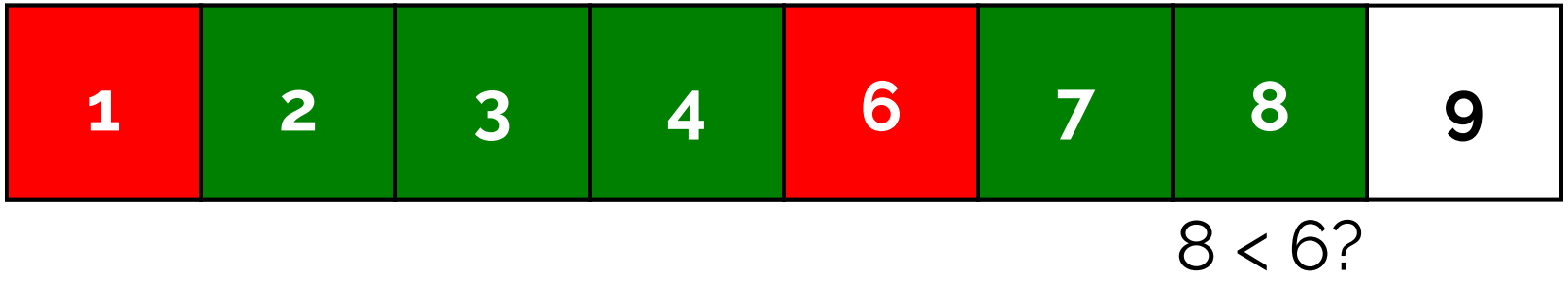
```
if (data[i] < 6) {
    ...
}
```



Prediction: Not taken

Simple branch predictor - sorted array

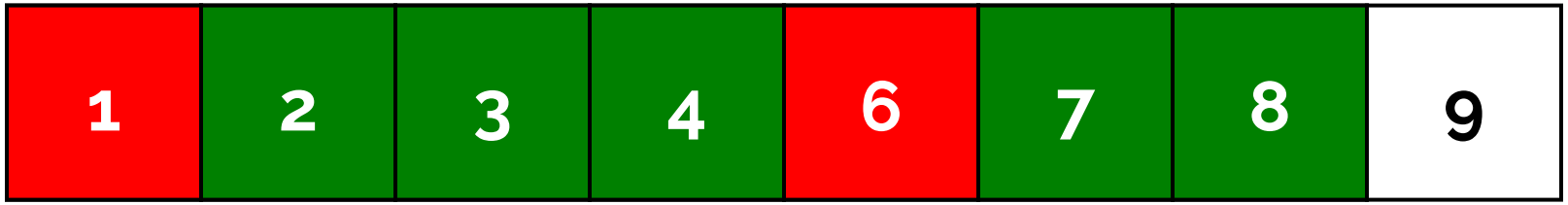
```
if (data[i] < 6) {
    ...
}
```



Prediction: Not taken

Simple branch predictor - sorted array

```
if (data[i] < 6) {
    ...
}
```

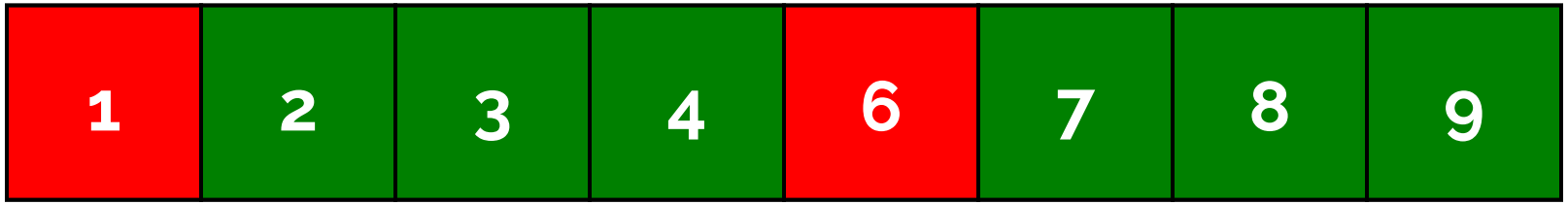


9 < 6?

Prediction: Not taken

Simple branch predictor - sorted array

```
if (data[i] < 6) {
    ...
}
```

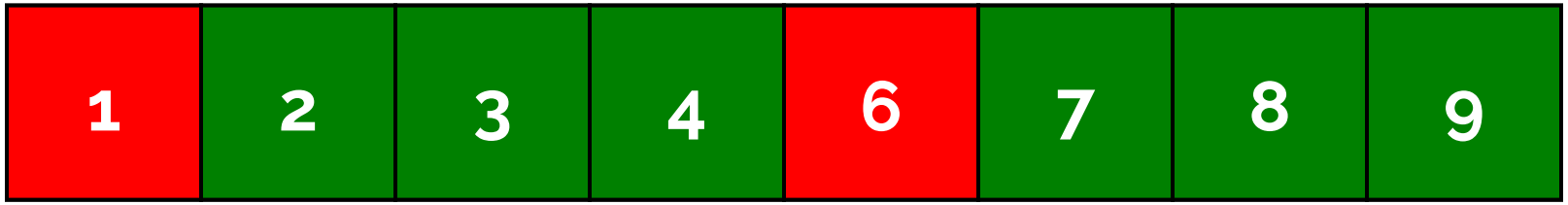


9 < 6?

Prediction: Not taken

Simple branch predictor - sorted array

```
if (data[i] < 6) {
    ...
}
```



Prediction: Not taken

6 hits, 2 misses (75% hit rate)

How can the compiler help?

```
float sum = 0;
for (auto _ : state)
{
    for (auto x : data)
    {
        if (x < 6)
        {
            sum += x;
        }
    }
}
```

```
47          mov     rax, rcx
48          cmp     rcx, rdx
49          je      .L9
50  .L12:
51          movss   xmm0, DWORD PTR [rax]
52          comiss  xmm2, xmm0
53          jbe     .L10
54          addss   xmm1, xmm0
55  .L10:
56          add     rax, 4
57          cmp     rdx, rax
58          jne     .L12
59  .L9:
60          sub     rbx, 1
61          jne     .L13
62          jmp     .L6
```

With `float`, there are two branches per iteration

How can the compiler help?

```
int sum = 0;
for (auto _ : state)
{
    for (auto x : data)
    {
        if (x < 6)
        {
            sum += x;
        }
    }
}
```

```
41  .L12:
42          mov     rax, r8
43          cmp     r8, rdi
44          je      .L9
45  .L11:
46          mov     edx, DWORD PTR [rax]
47          cmp     edx, 6
48          lea     ecx, [rbx+rdx]
49          cmovl   ebx, ecx
50          add     rax, 4
51          cmp     rdi, rax
52          jne     .L11
53  .L9:
54          sub     rbp, 1
55          jne     .L12
56          mov     rdi, r12
```

With `int`, one branch is removed (using `cmov`)

How to measure?

`branch-misses`

How many times was a branch mispredicted?

How to measure?

`branch-misses`

How many times was a branch mispredicted?

```
$ perf stat -e branch-misses ./example0a
with    sort ->     383 902
without sort -> 101 652 009
```

How to help the branch predictor?

- More predictable data

How to help the branch predictor?

- More predictable data
- Profile-guided optimization

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- More predictable data
- Profile-guided optimization
- Remove (unpredictable) branches

How to help the branch predictor?

- More predictable data
- Profile-guided optimization
- Remove (unpredictable) branches
- Compiler hints (use with caution)

```
if (__builtin_expect(will_it_blend(), 0)) {
    // this branch is not likely to be taken
}
```

Branch target prediction

- Target of a jump is not known at compile time:

Branch target prediction

- Target of a jump is not known at compile time:
  - Function pointer

Branch target prediction

- Target of a jump is not known at compile time:
  - Function pointer
  - Function return address

Branch target prediction

- Target of a jump is not known at compile time:
  - Function pointer
  - Function return address
  - Virtual method

Code (backup)

```
struct A { virtual void handle(size_t* data) const = 0; };
struct B: public A { void handle(size_t* data) const final { *data += 1; } };
struct C: public A { void handle(size_t* data) const final { *data += 2; } };

std::vector<std::unique_ptr<A>> data = /* 4K random B/C instances */;
// std::sort(data.begin(), data.end(), /* sort by instance type */);
size_t sum = 0;
for (auto& x : data)
{
    x->handle(&sum);
}
```

Result (backup)

```
-----------------------------------------------------------------
Benchmark                       Time             CPU   Iterations
-----------------------------------------------------------------
handle_nosort/4096          23350 ns        23349 ns        30734
handle_sorted/4096           7448 ns         7448 ns        86814
```

perf (backup)

```
$ perf stat -e branch-misses ./example0b
with sort    ->      337 274
without sort -> 84 183 161
```

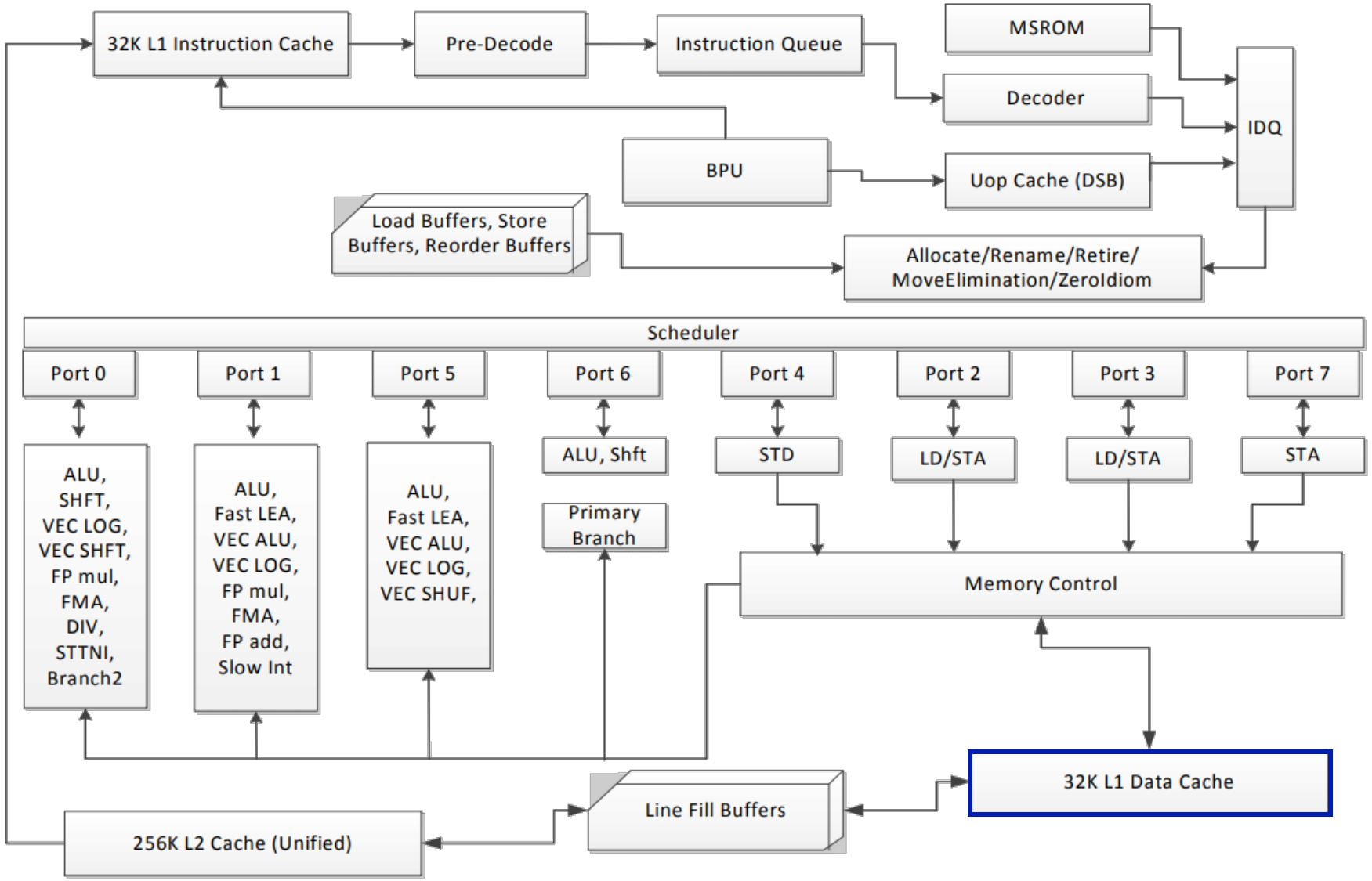
Code (backup)

```
// Addresses of N integers, each `offset` bytes apart
std::vector<int*> data = ...;
for (auto ptr: data)
{
    *ptr += 1;
}
// Offsets: 4, 64, 4000, 4096, 4128
```

Result (backup)

Benchmark	Time	CPU	Iterations
offset4/7	2.83 ns	2.83 ns	255750233
offset4/8	3.03 ns	3.02 ns	177109965
offset4/9	3.76 ns	3.75 ns	157739295
offset4/10	4.62 ns	4.61 ns	177899906
offset4/11	4.93 ns	4.92 ns	162959140
offset64/7	3.19 ns	3.18 ns	179723151
offset64/8	3.83 ns	3.65 ns	216288609
offset64/9	3.74 ns	3.74 ns	201008685
offset64/10	4.41 ns	4.40 ns	159949703
offset64/11	4.41 ns	4.41 ns	128933855
offset4000/7	3.69 ns	3.69 ns	187745245
offset4000/8	3.27 ns	3.26 ns	226401022
offset4000/9	4.19 ns	4.18 ns	157866983
offset4000/10	4.49 ns	4.48 ns	173084452
offset4000/11	4.53 ns	4.52 ns	128906229
offset4096/7	9.05 ns	9.05 ns	78087527
offset4096/8	10.4 ns	10.4 ns	67550724
offset4096/9	18.7 ns	18.7 ns	38875870
offset4096/10	25.5 ns	25.5 ns	26893946
offset4096/11	32.7 ns	32.7 ns	21369400
offset4128/7	3.23 ns	3.22 ns	250263727
offset4128/8	3.13 ns	3.13 ns	218371877
offset4128/9	3.75 ns	3.71 ns	157448182
offset4128/10	4.28 ns	4.25 ns	144839049
offset4128/11	5.47 ns	5.44 ns	128547528

Cache memory



How are (L1) caches implemented

- N-way set associative table
  - Hardware hash table

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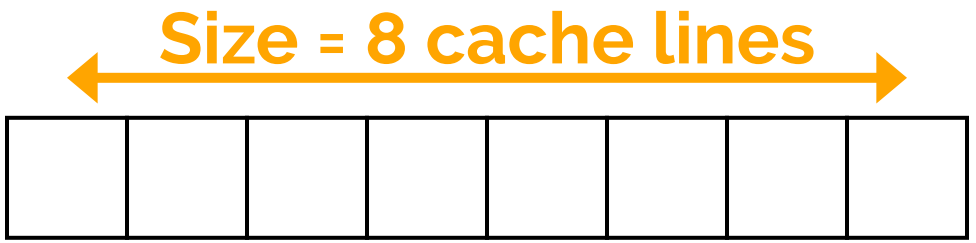
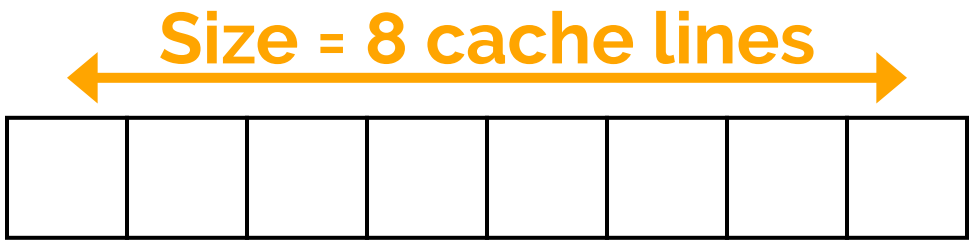
How are (L1) caches implemented

- N-way set associative table
  - Hardware hash table
- Key = address (8B)
- Entry = cache line (64B)

N-way set associative cache

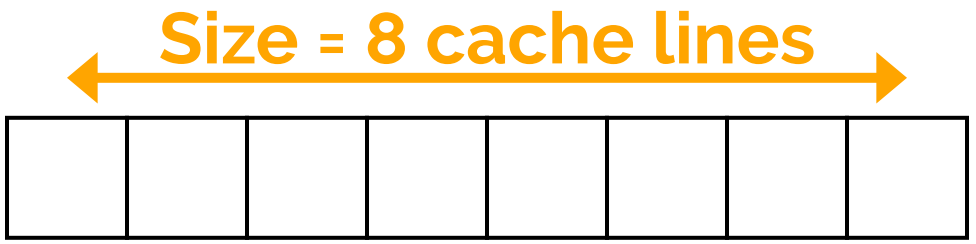


N-way set associative cache



Associativity (N) - # of cache lines per bucket

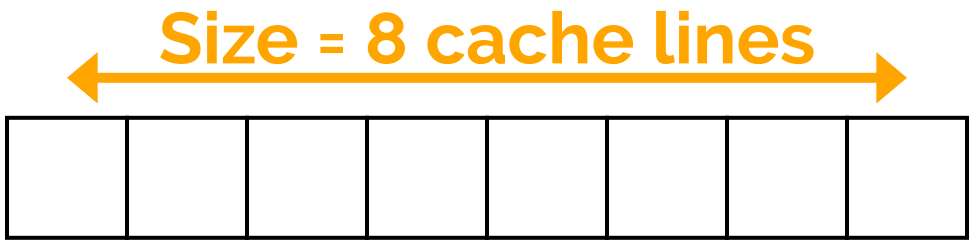
N-way set associative cache



Associativity (N) - # of cache lines per bucket

# of buckets = Size / N

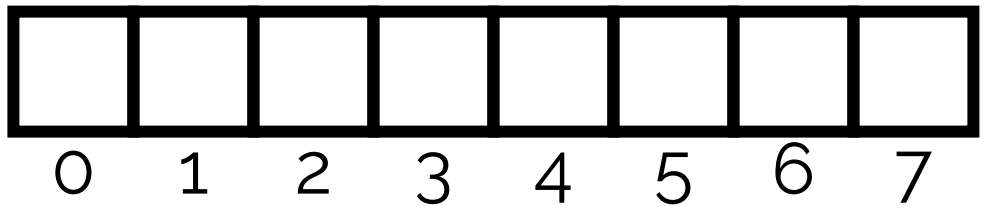
N-way set associative cache



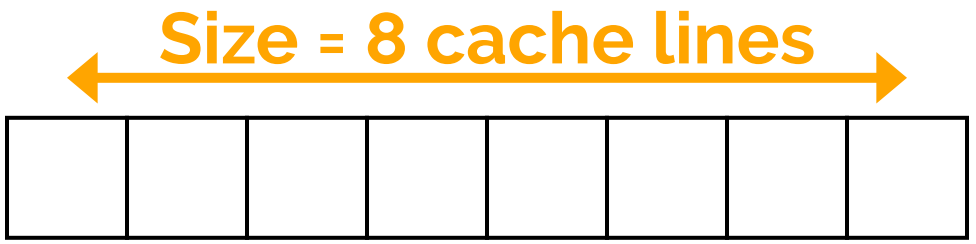
Associativity (N) - # of cache lines per bucket

# of buckets = Size / N

N = 1 (direct mapped)



N-way set associative cache



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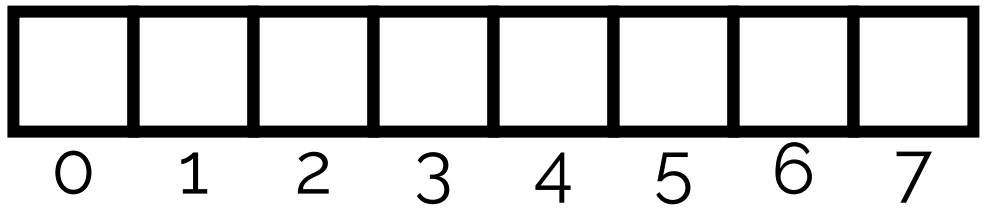
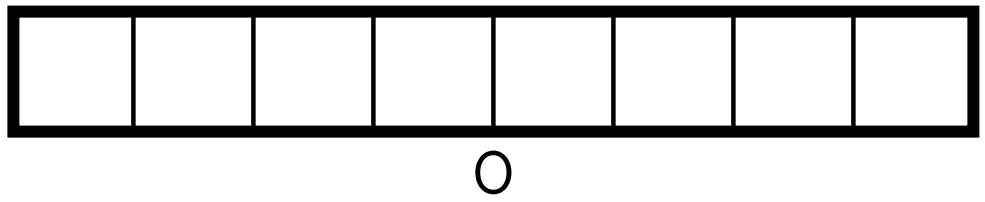
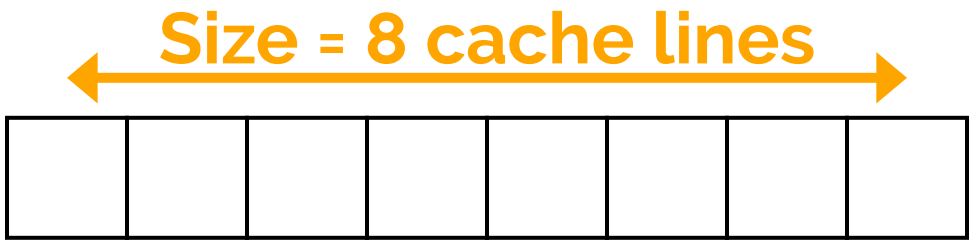


N = 8 (fully associative)



N-way set associative cache



Associativity (N) - # of cache lines per bucket

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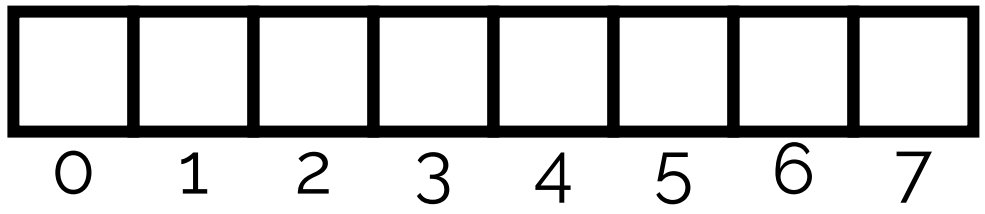

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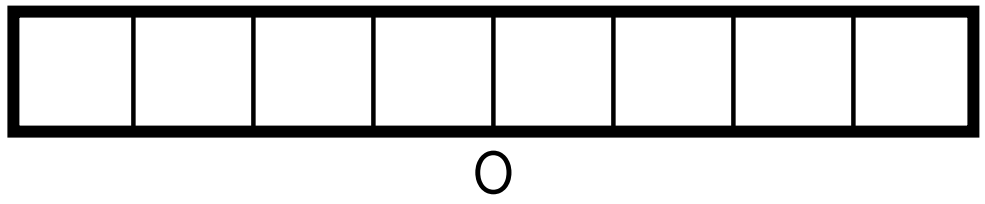
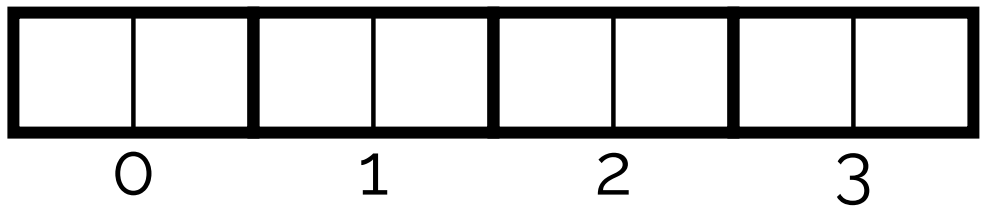


N = 2



How are addresses hashed?

How are addresses hashed?

- **Offset**
  - Selects byte within a cache line
  - log2(cache line size) bits

How are addresses hashed?

- **Offset**
  - Selects byte within a cache line
  - log2(cache line size) bits
- **Index**
  - Selects bucket within the cache
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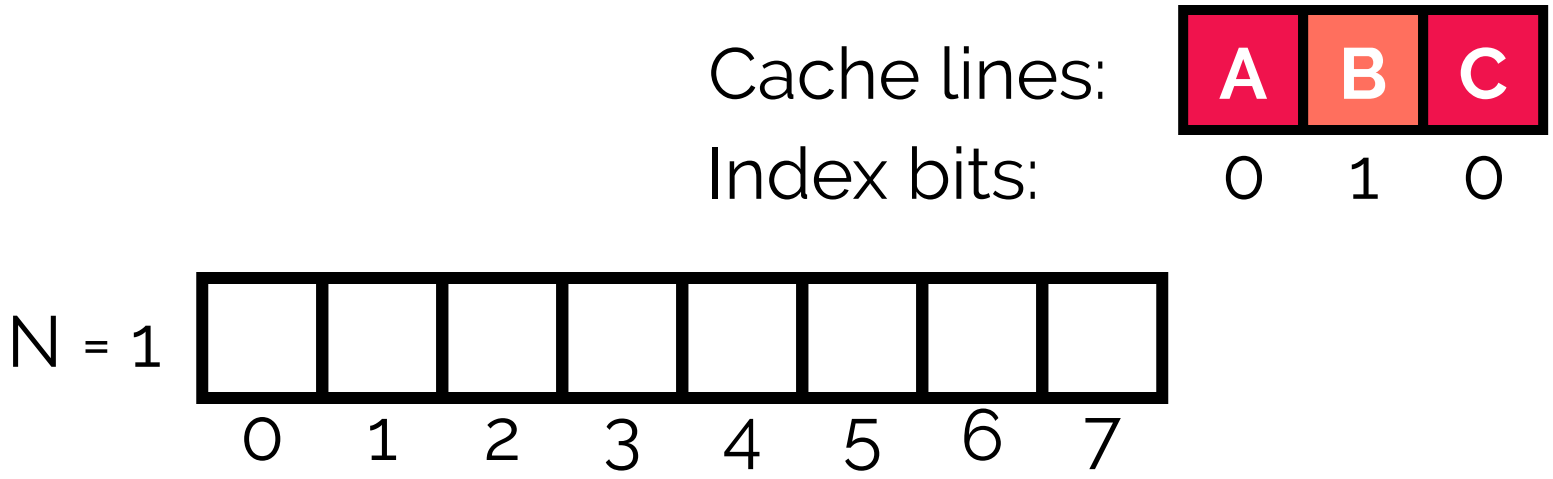
How are addresses hashed?

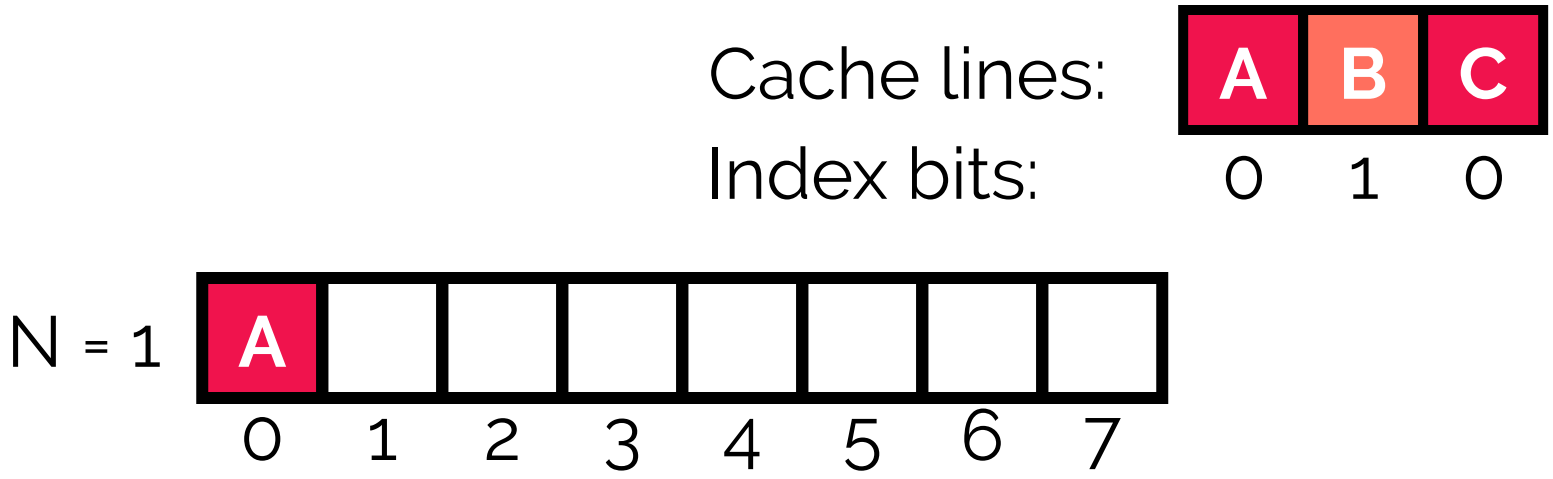
- **Offset**
  - Selects byte within a cache line
  - log2(cache line size) bits
- **Index**
  - Selects bucket within the cache
  - log2(bucket count) bits
- **Tag**
  - Used for matching

N-way set associative cache

N-way set associative cache



N-way set associative cache



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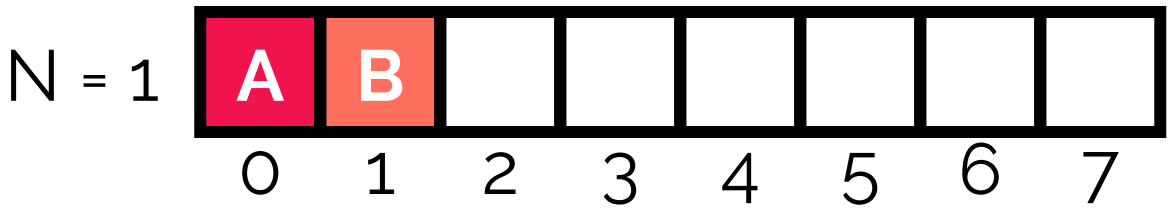

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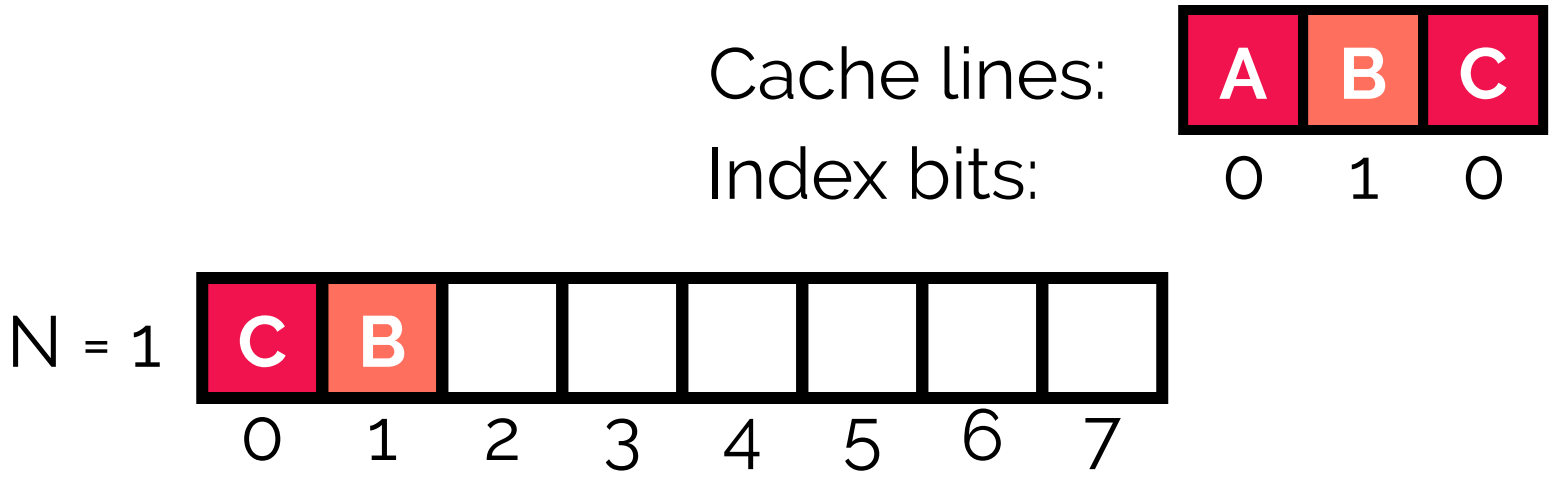

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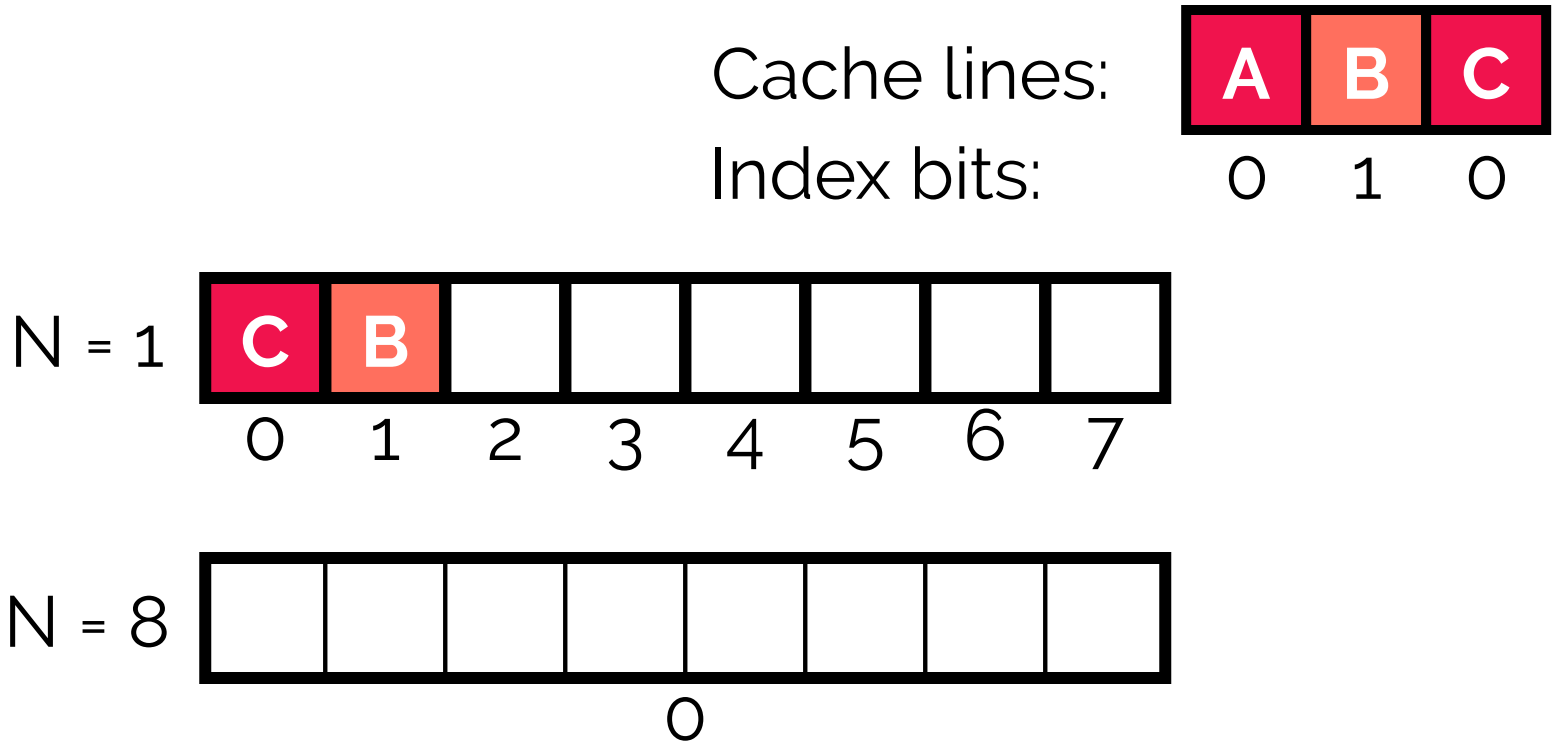

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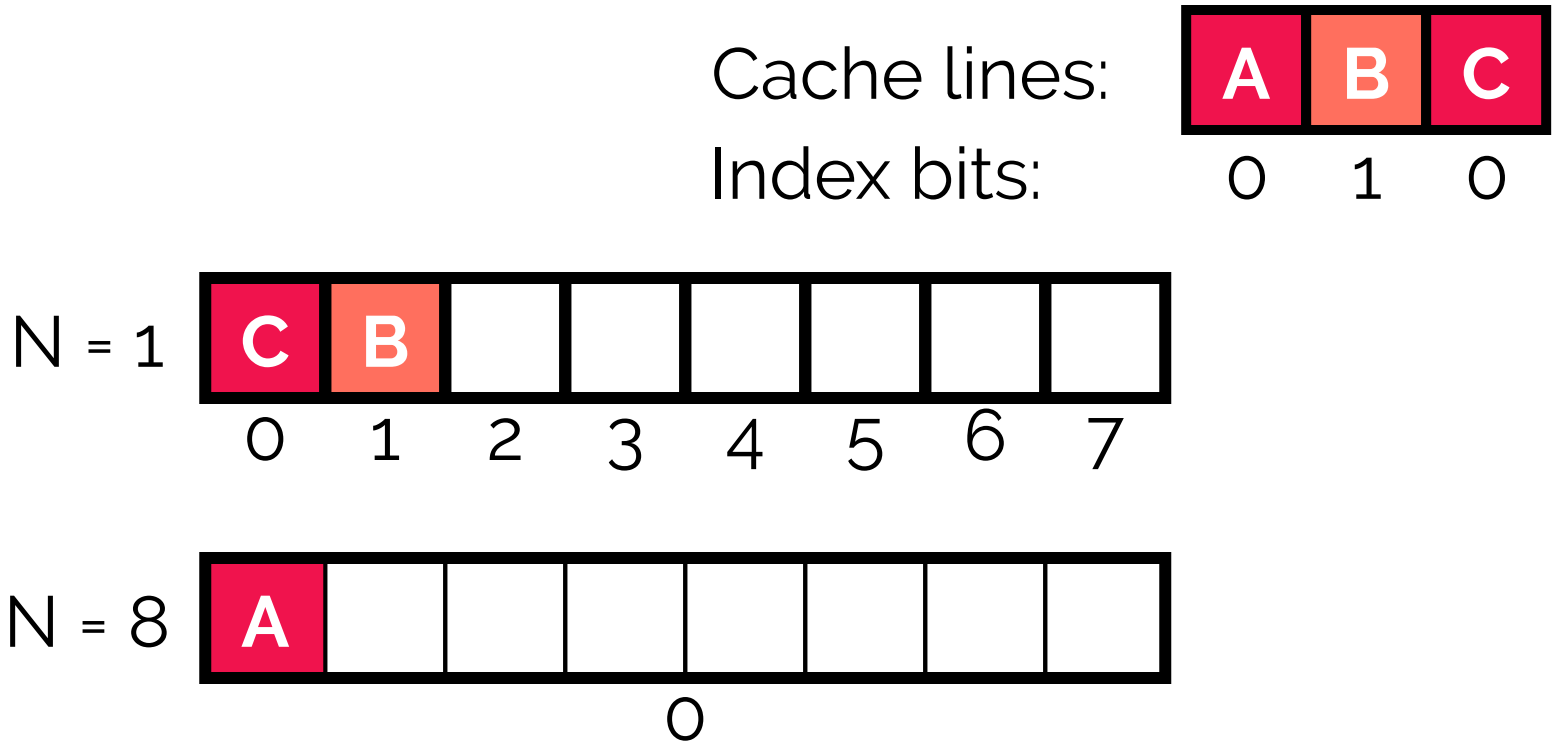

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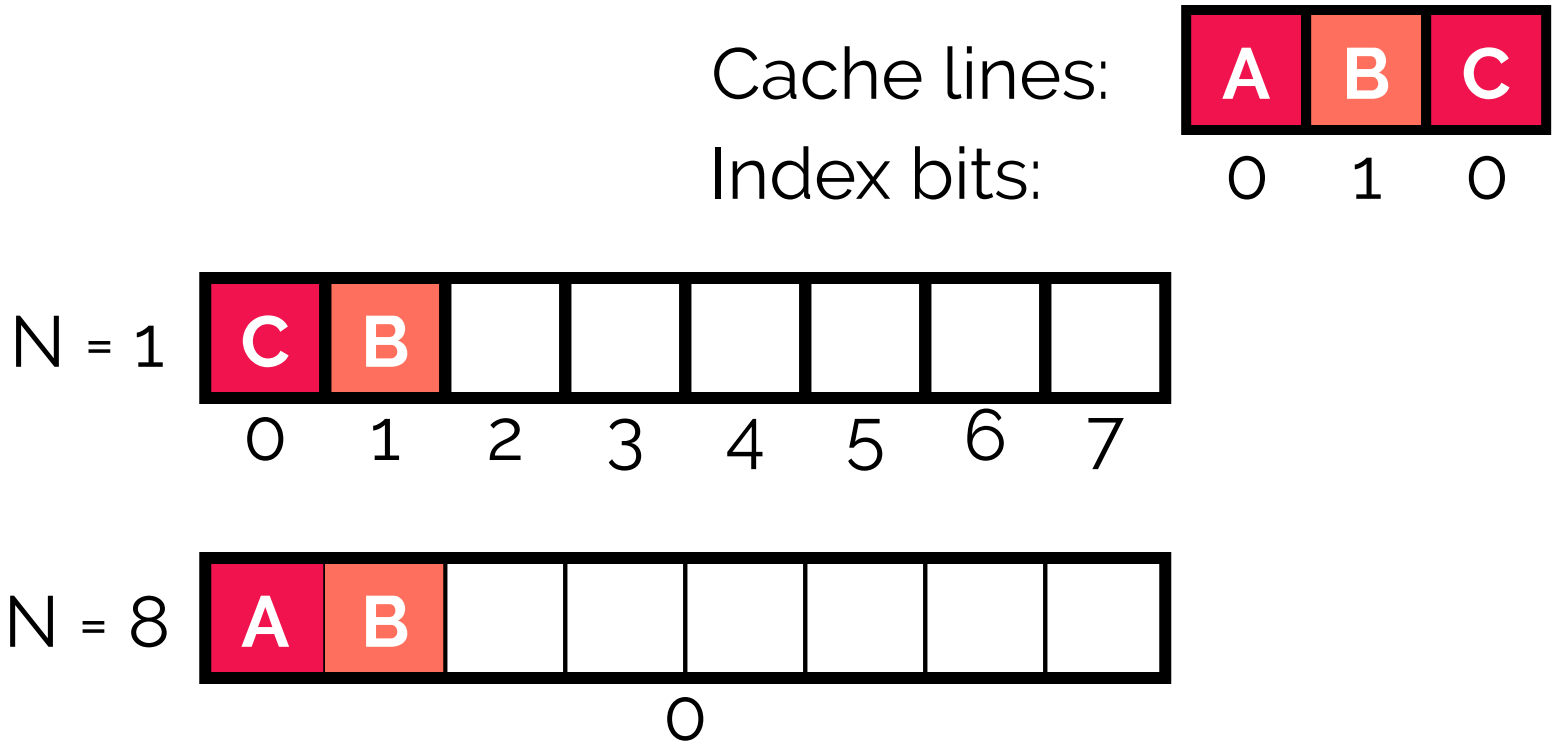

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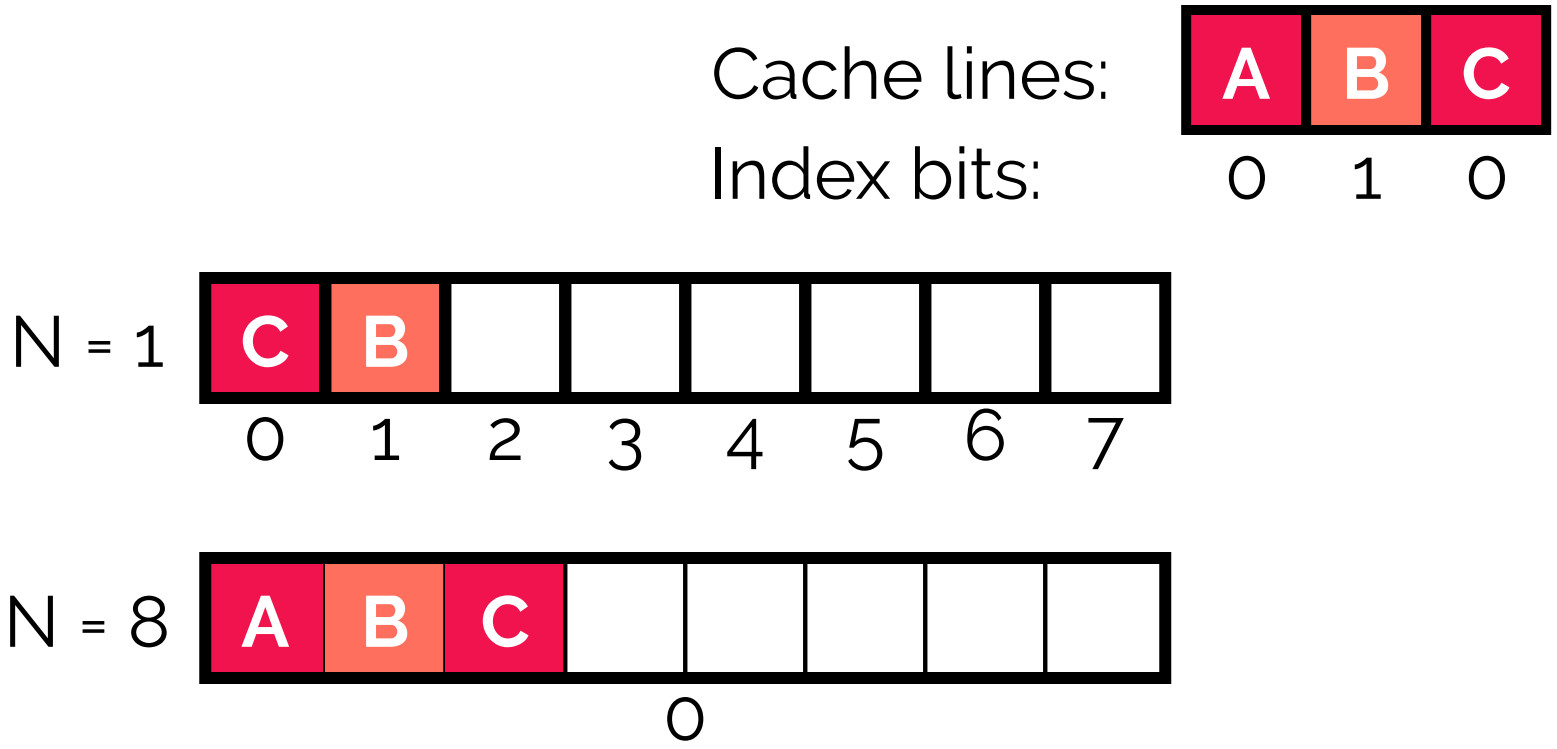
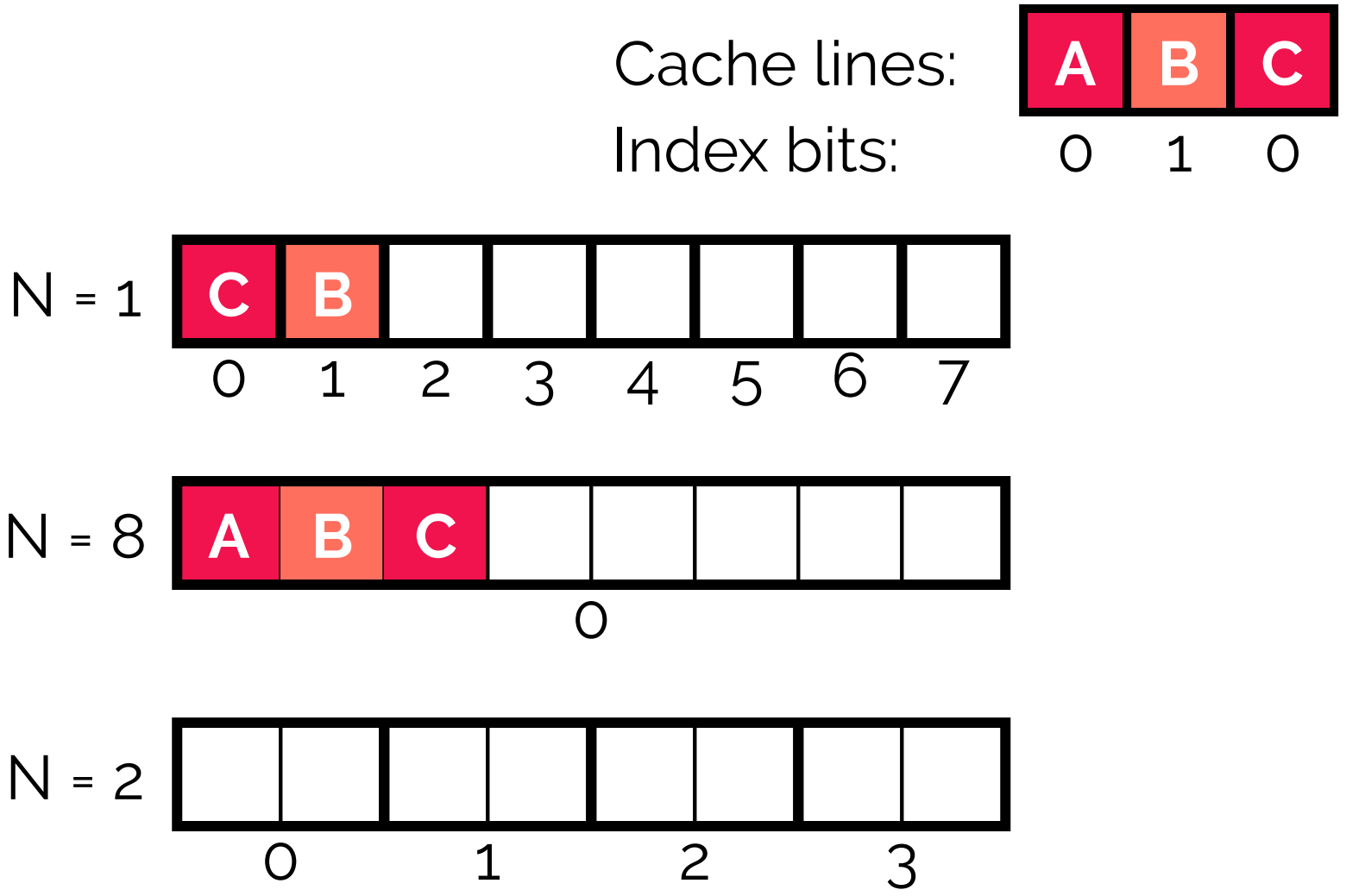
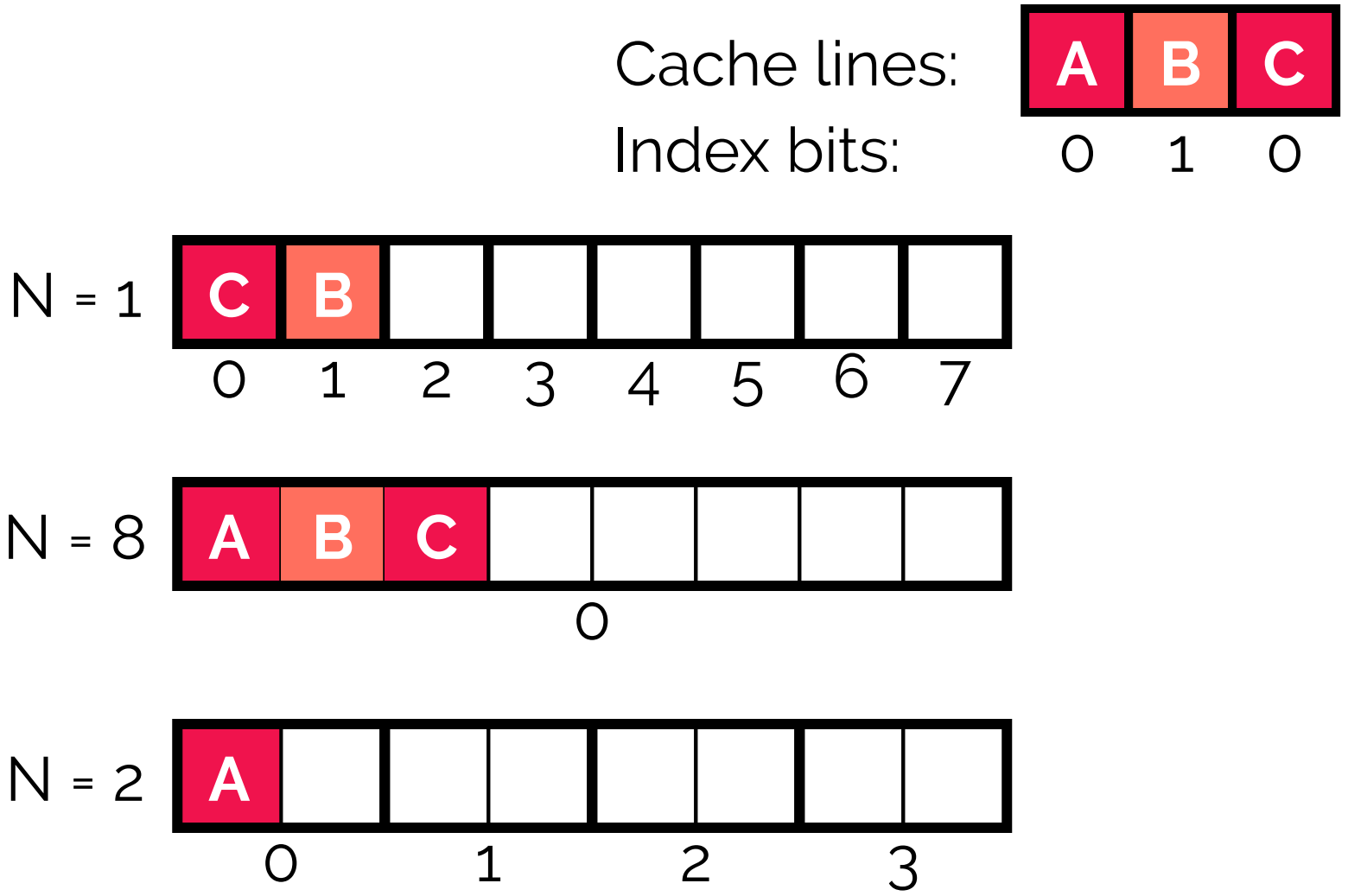


N-way set associative cache



N-way set associative cache



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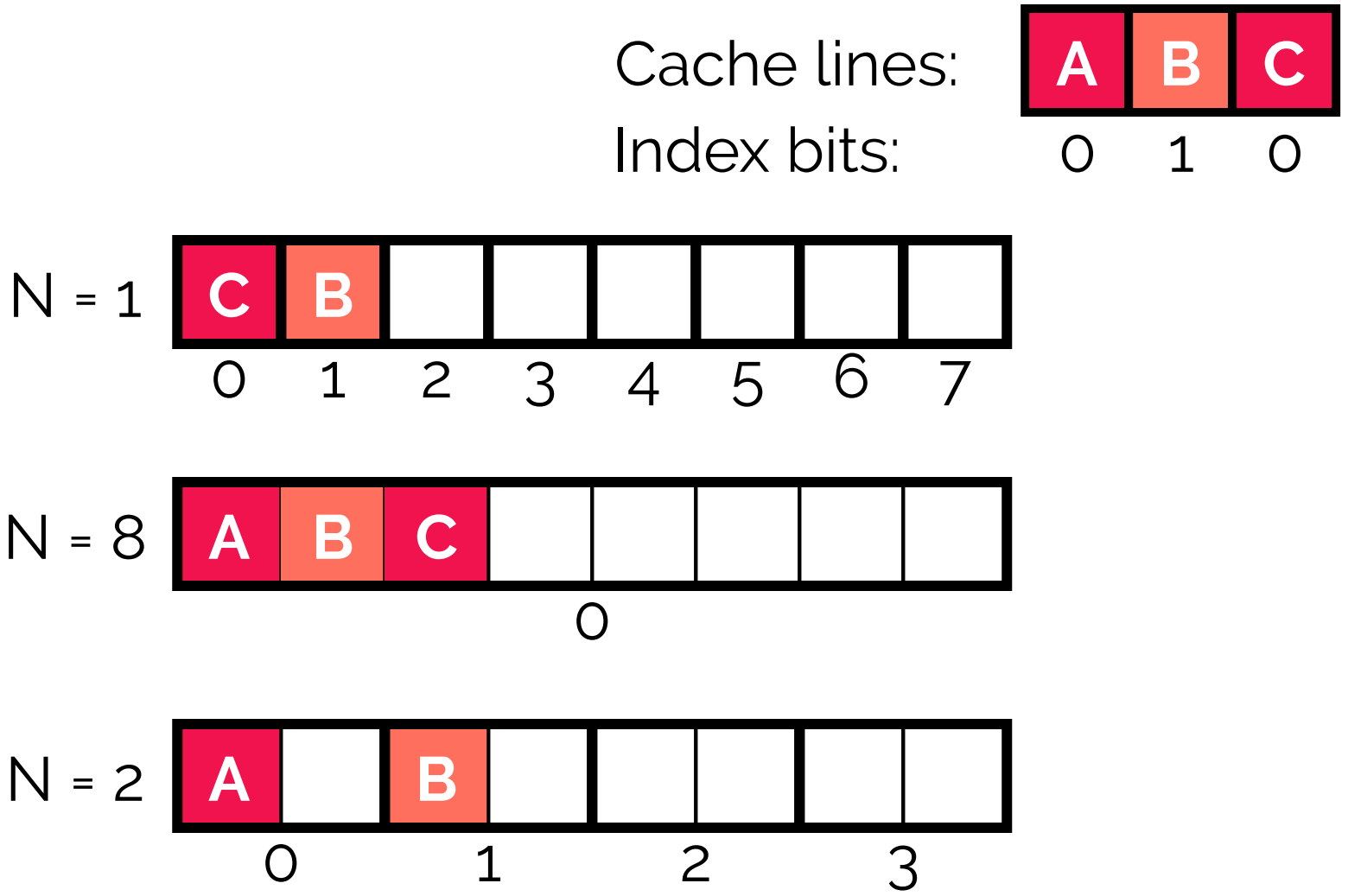
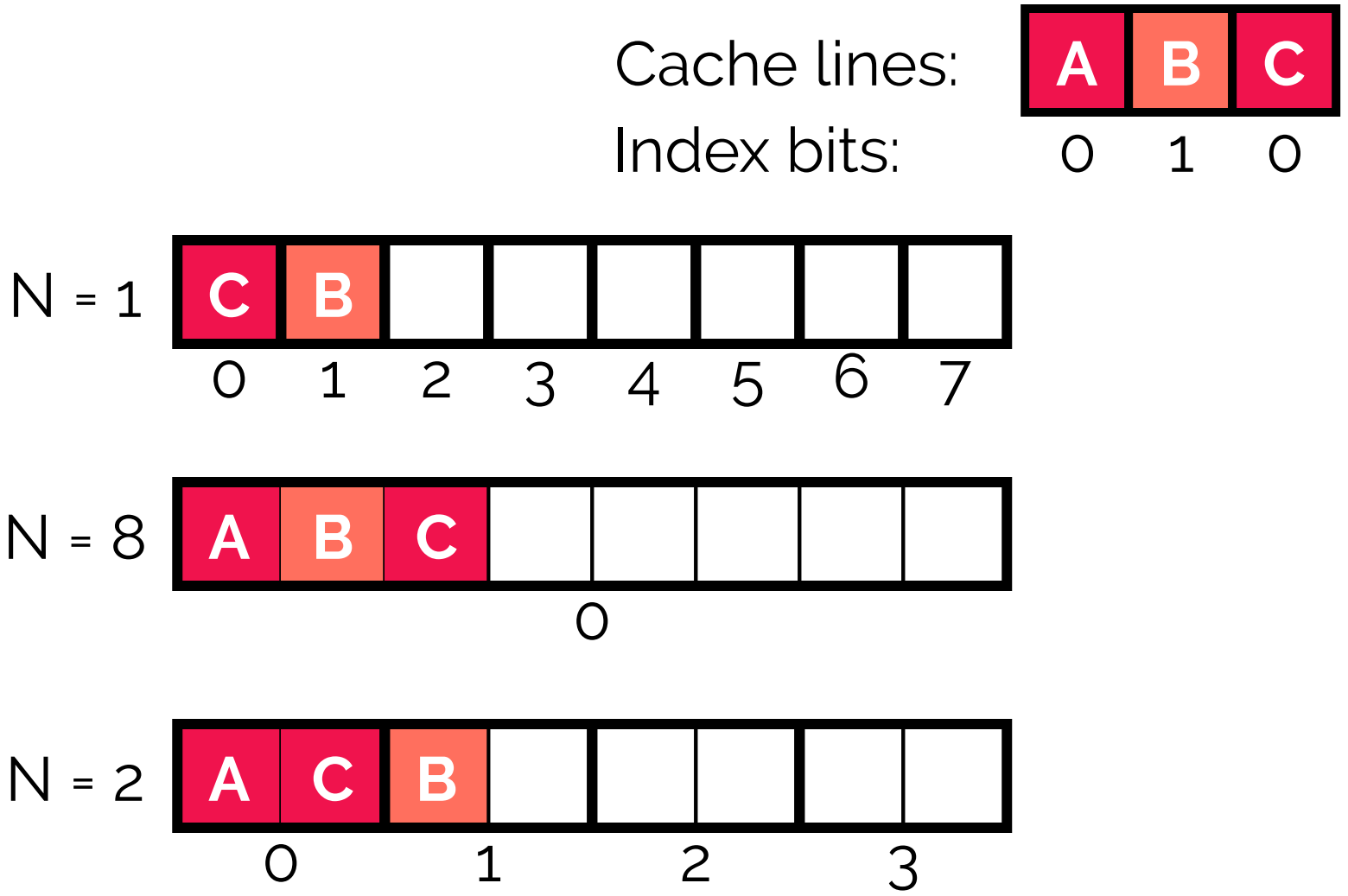


N-way set associative cache



Intel L1 cache

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LEVEL1_DCACHE_SIZE          32768
LEVEL1_DCACHE_ASSOC         8
LEVEL1_DCACHE_LINESIZE      64
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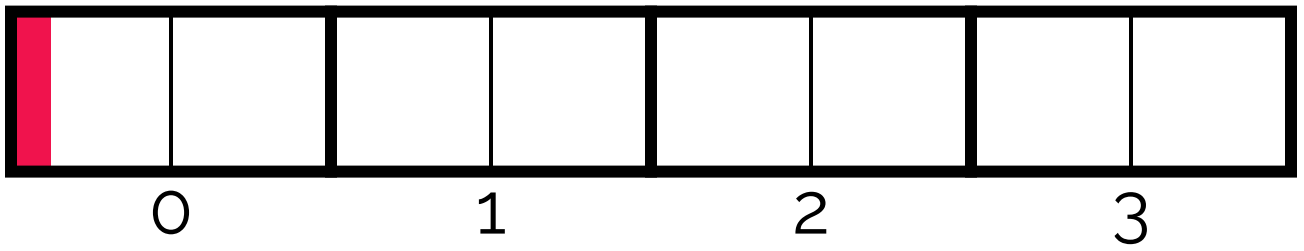
```

- **Cache line size** - 64 B (6 offset bits)
- **Associativity** (N) - 8
- **Size** - 32768 B
- 32768 / 64 => 512 cache lines
- 512 / 8 => 64 buckets (6 index bits)

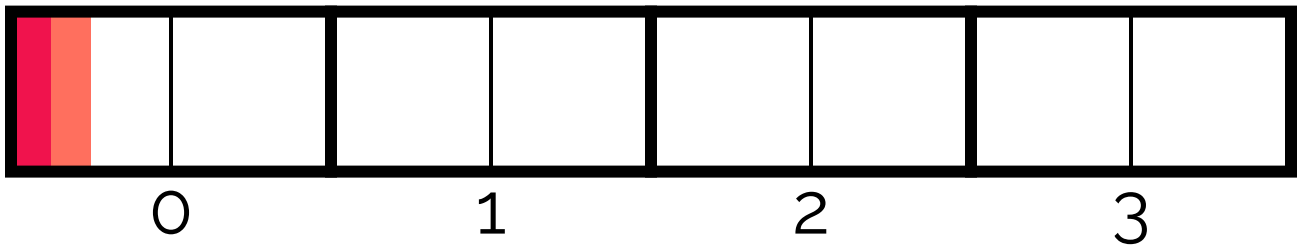
Offset = 4B

Number	Tag	Index	Offset
A	..100000	000000	000000



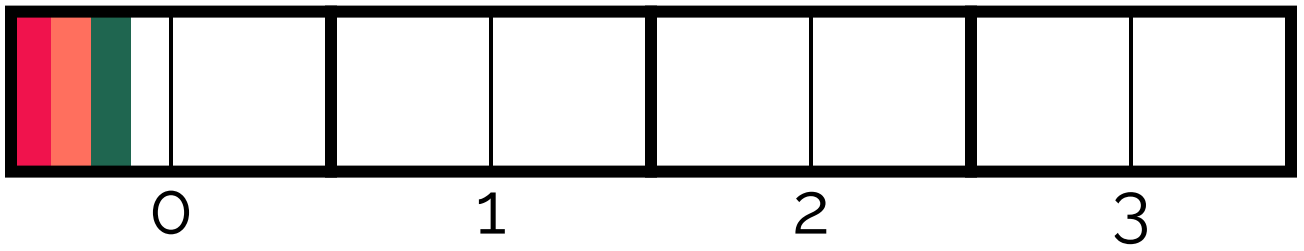
Offset = 4B

Number	Tag	Index	Offset
A	..100000	000000	000000
B	..100000	000000	000100



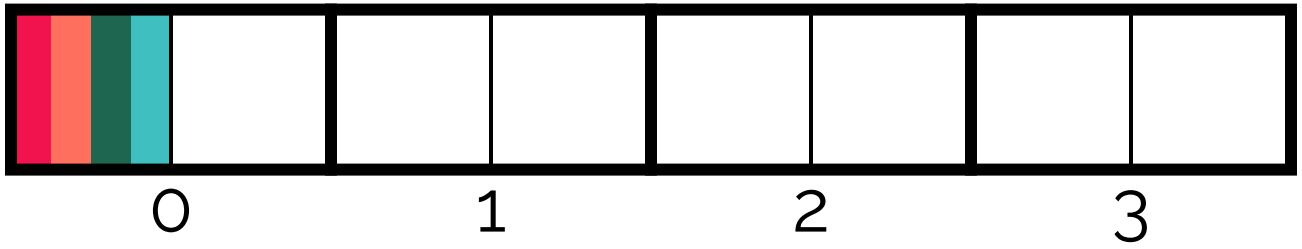
Offset = 4B

Number	Tag	Index	Offset
A	..100000	000000	000000
B	..100000	000000	000100
C	..100000	000000	001000



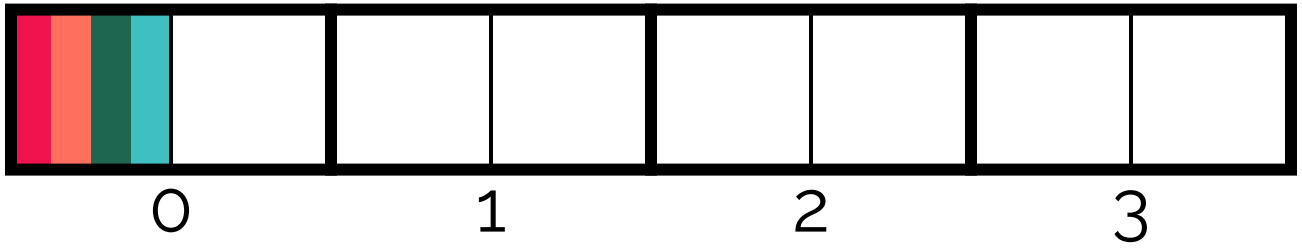
Offset = 4B

Number	Tag	Index	Offset
A	..100000	000000	000000
B	..100000	000000	000100
C	..100000	000000	001000
D	..100000	000000	001100



Offset = 4B

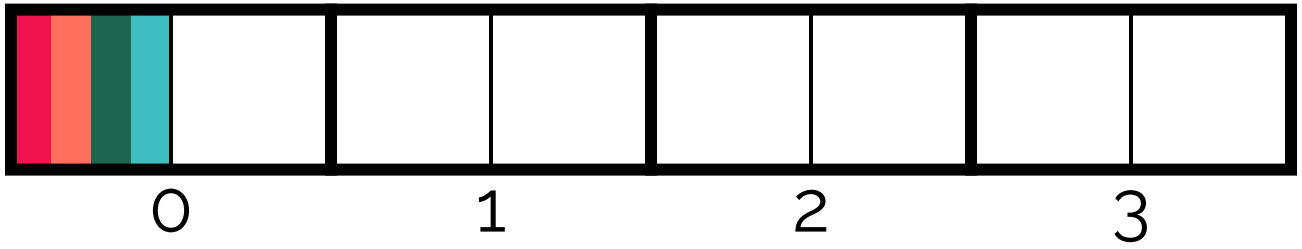
Number	Tag	Index	Offset
A	..100000	000000	000000
B	..100000	000000	000100
C	..100000	000000	001000
D	..100000	000000	001100



- Same bucket, same cache line for each number

Offset = 4B

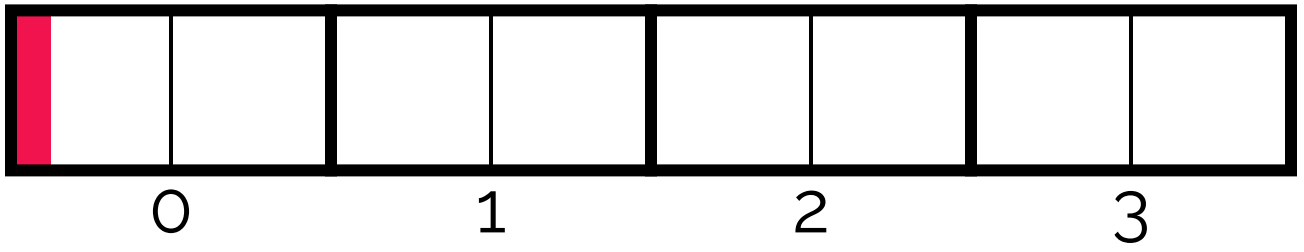
Number	Tag	Index	Offset
A	..100000	000000	000000
B	..100000	000000	000100
C	..100000	000000	001000
D	..100000	000000	001100



- Same bucket, same cache line for each number
- Most efficient, no space is wasted

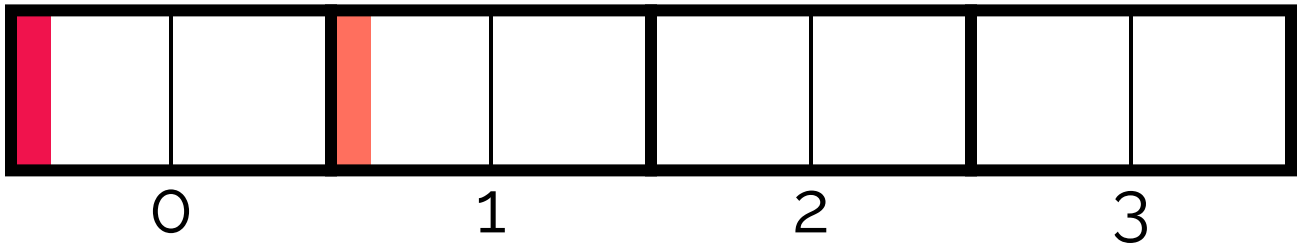
Offset = 64B

Number	Tag	Index	Offset
A	..100000	000000	000000



Offset = 64B

Number	Tag	Index	Offset
A	..100000	000000	000000
B	..100000	000001	000000



Offset = 64B

Number	Tag	Index	Offset
A	..100000	000000	000000
B	..100000	000001	000000
C	..100000	000010	000000

Offset = 64B

Number	Tag	Index	Offset
A	..100000	000000	000000
B	..100000	000001	000000
C	..100000	000010	000000
D	..100000	000011	000000

Offset = 64B

Number	Tag	Index	Offset
A	..100000	000000	000000
B	..100000	000001	000000
C	..100000	000010	000000
D	..100000	000011	000000

- Different bucket for each number

Offset = 64B

Number	Tag	Index	Offset
A	..100000	000000	000000
B	..100000	000001	000000
C	..100000	000010	000000
D	..100000	000011	000000

- Different bucket for each number
- Wastes 60B in each cache line

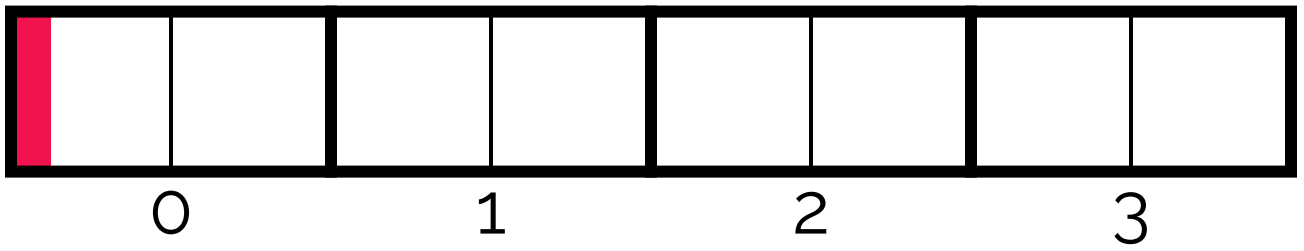
Offset = 64B

Number	Tag	Index	Offset
A	..100000	000000	000000
B	..100000	000001	000000
C	..100000	000010	000000
D	..100000	000011	000000

- Different bucket for each number
- Wastes 60B in each cache line
- Equally distributed among buckets

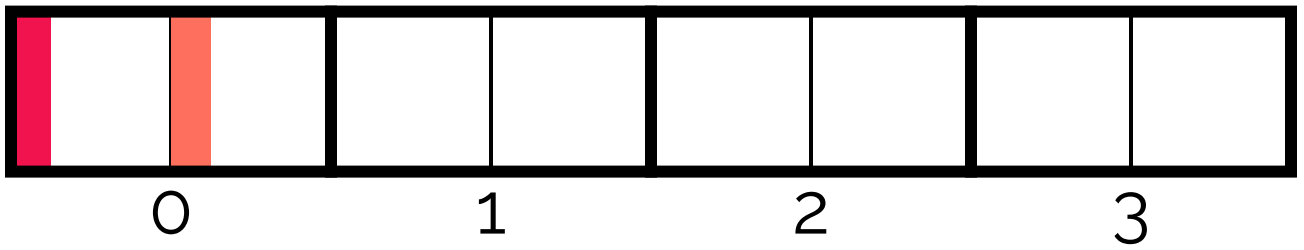
Offset = 4096B

Number	Tag	Index	Offset
A	..100000	000000	000000



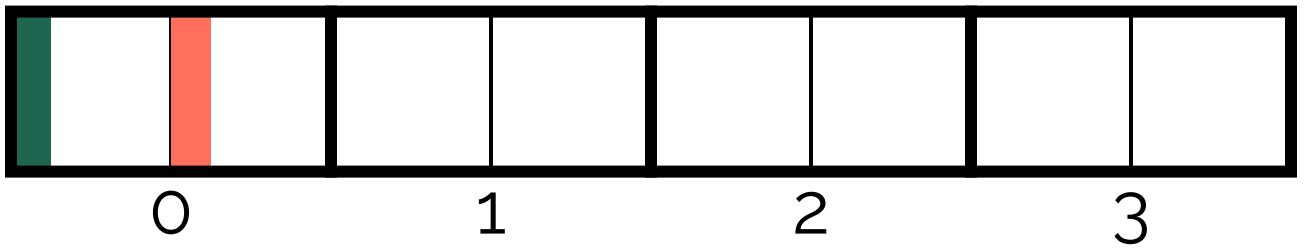
Offset = 4096B

Number	Tag	Index	Offset
A	..100000	000000	000000
B	..100001	000000	000000



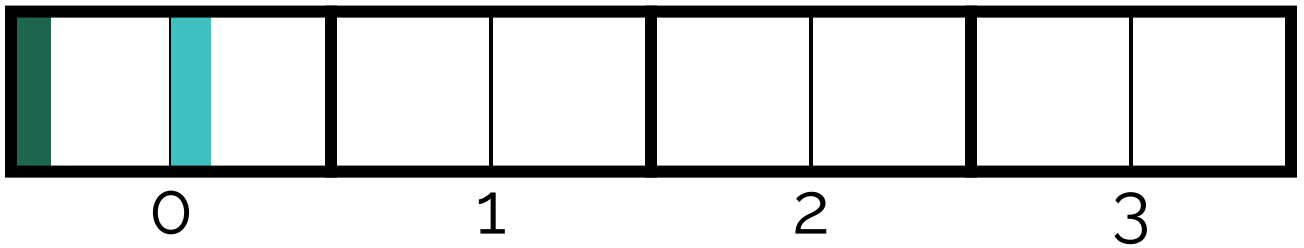
Offset = 4096B

Number	Tag	Index	Offset
A	..100000	000000	000000
B	..100001	000000	000000
C	..100010	000000	000000



Offset = 4096B

Number	Tag	Index	Offset
A	..100000	000000	000000
B	..100001	000000	000000
C	..100010	000000	000000
D	..100011	000000	000000



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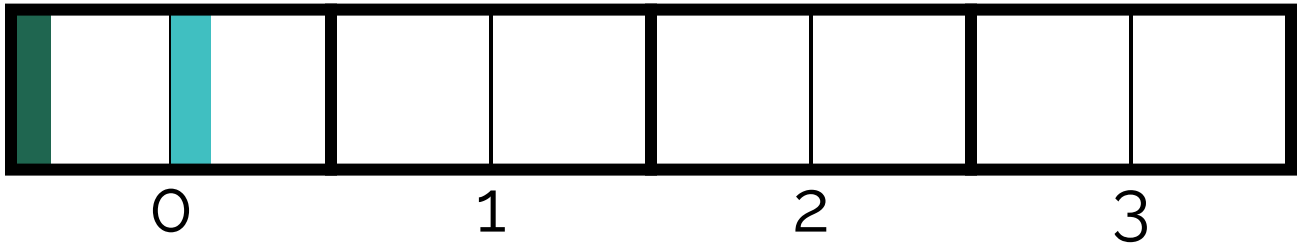
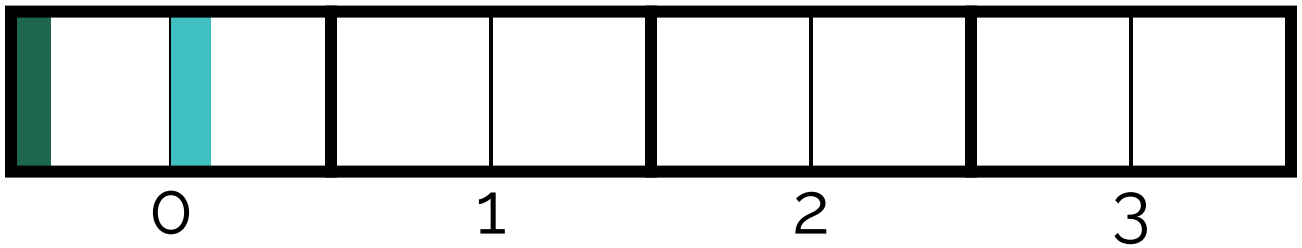
Number	Tag	Index	Offset
A	..100000	000000	000000
B	..100001	000000	000000
C	..100010	000000	000000
D	..100011	000000	000000



- Same bucket, but different cache lines for each number!

Offset = 4096B

Number	Tag	Index	Offset
A	..100000	000000	000000
B	..100001	000000	000000
C	..100010	000000	000000
D	..100011	000000	000000



- Same bucket, but different cache lines for each number!
- Bucket full => evictions necessary

How to measure?

`l1d.replacement`

How many times was a cache line loaded into L1?

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`l1d.replacement`

How many times was a cache line loaded into L1?

```
$ perf stat -e l1d.replacement ./example1
4B    offset ->      149 558
4096B offset -> 426 218 383
```

Code (backup)

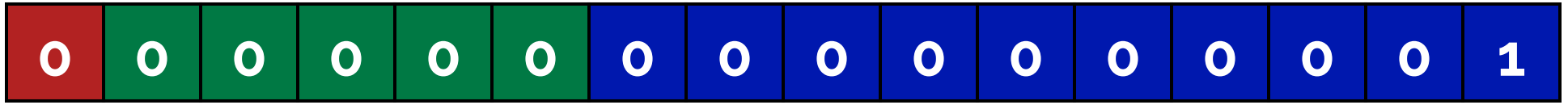
```
float F = static_cast<float>(std::stof(argv[1]));
std::vector<float> data(4 * 1024 * 1024, 1);

for (int r = 0; r < 100; r++)
{
    for (auto& item: data)
    {
        item *= F;
    }
}
```

Result (backup)

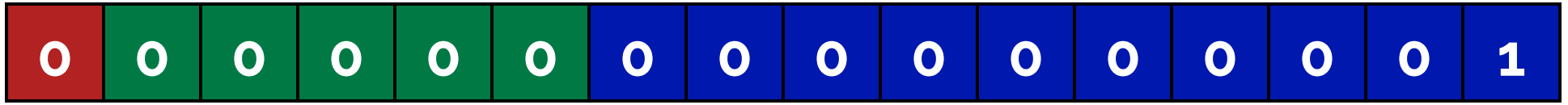
```
> time -p ./example2 0
real 0,12
user 0,12
sys 0,00
> time -p ./example2 0.1
real 0,47
user 0,46
sys 0,00
> time -p ./example2 0.3
real 0,70
user 0,69
sys 0,00
```

Denormal floating point numbers



$$(-1)^{0} * 2^{00000-\mathbf{01110}} * \mathbf{0}.0000000001$$

Denormal floating point numbers



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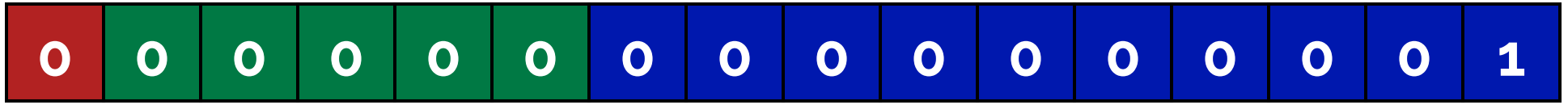

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- Numbers close to zero
- Hidden bit = 0, smaller bias

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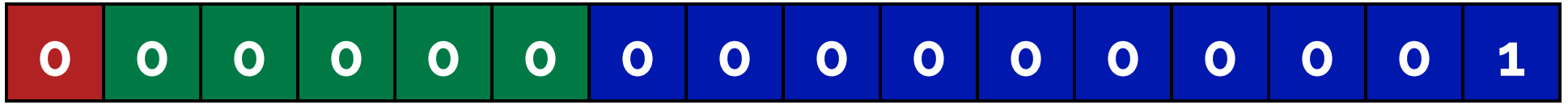
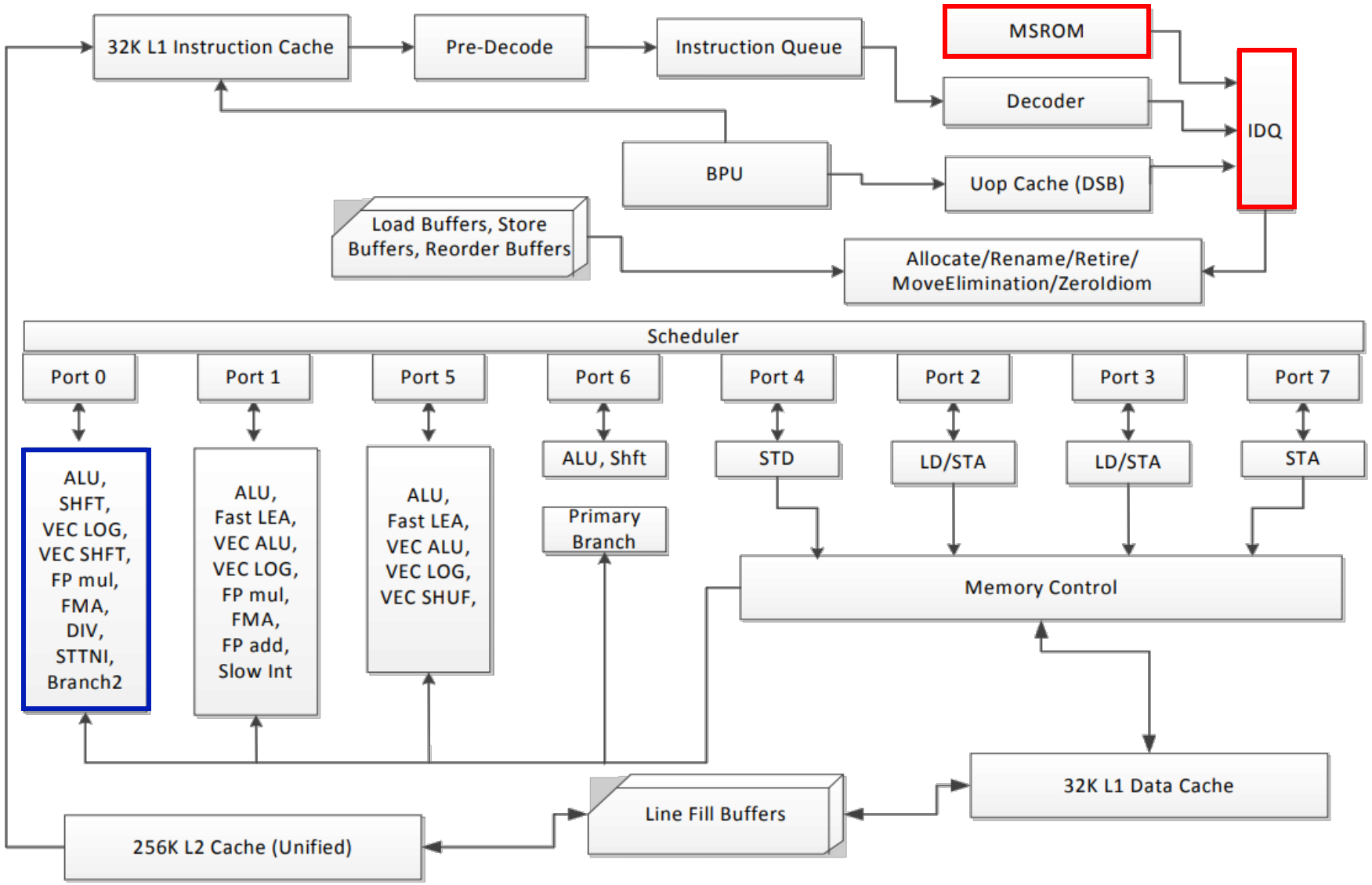


$$(-1)^{0} * 2^{00000-\mathbf{01110}} * \mathbf{0}.0000000001$$

- Numbers close to zero
- Hidden bit = 0, smaller bias

Operations on denormal numbers are slow!

Floating point handling



How to measure?

`fp_assist.any`

How many times the CPU switched to the microcode FP handler?

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`fp_assist.any`

How many times the CPU switched to the microcode FP handler?

```
$ perf stat -e fp_assist.any ./example2
0    ->              0
0.3 -> 15 728 640
```

How to fix it?

- The nuclear option: `-ffast-math`
  - Sacrifice correctness to gain more FP performance

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- The nuclear option: `-ffast-math`
  - Sacrifice correctness to gain more FP performance
- Set CPU flags:
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  - Denormals-to-zero - treat denormal inputs as 0

How to fix it?

- The nuclear option: `-ffast-math`
  - Sacrifice correctness to gain more FP performance
- Set CPU flags:
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  - Denormals-to-zero - treat denormal inputs as 0

```
_mm_setcsr(_mm_getcsr() | 0x8040);
// or
_MM_SET_FLUSH_ZERO_MODE(_MM_FLUSH_ZERO_ON);
_MM_SET_DENORMALS_ZERO_MODE(_MM_DENORMALS_ZERO_ON);
```

There are many other effects

- NUMA
- 4k aliasing
- Misaligned accesses, cache line boundaries
- Instruction data dependencies
- Software prefetching
- Non-temporal stores & cache pollution
- Bandwidth saturation
- DRAM refresh intervals
- AVX/SSE transition penalty
- ...

Thank you!

For more examples visit:
`github.com/kobzol/hardware-effects`

Jakub Beránek

Slides built with `github.com/spirali/elsie`

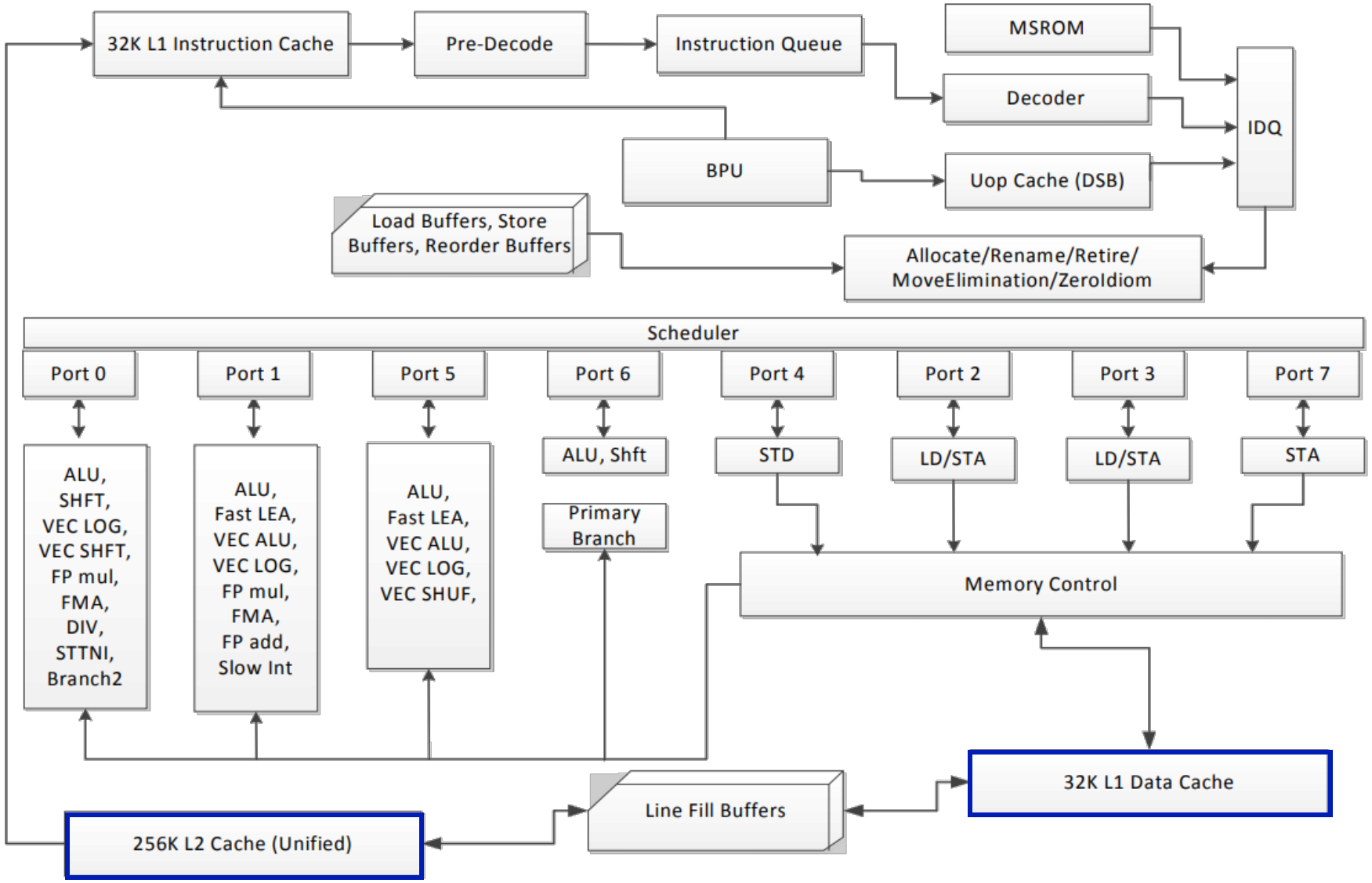
Code (backup)

```
// tid - [0, NO_OF_THREADS)
void thread_fn(int tid, double* data)
{
    size_t repetitions = 1024 * 1024 * 1024UL;
    for (size_t i = 0; i < repetitions; i++)
    {
        data[tid] *= i;
    }
}
```

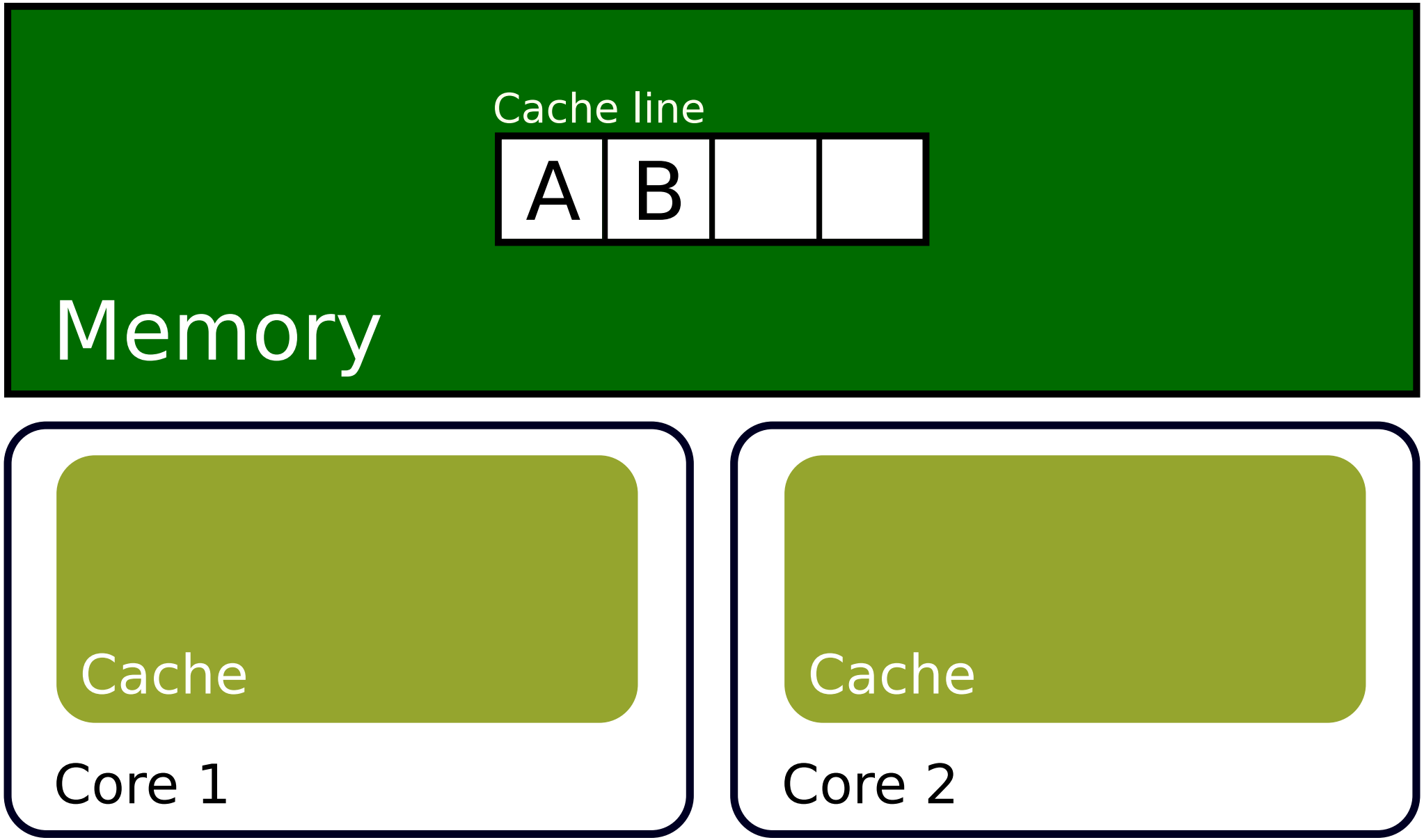
Result (backup)

```
> time -p ./example2 1
real 2,60
user 2,60
sys 0,00
> time -p ./example2 2
real 2,92
user 5,83
sys 0,00
> time -p ./example2 3
real 3,15
user 9,04
sys 0,01
> time -p ./example2 4
real 3,39
user 13,44
sys 0,00
```

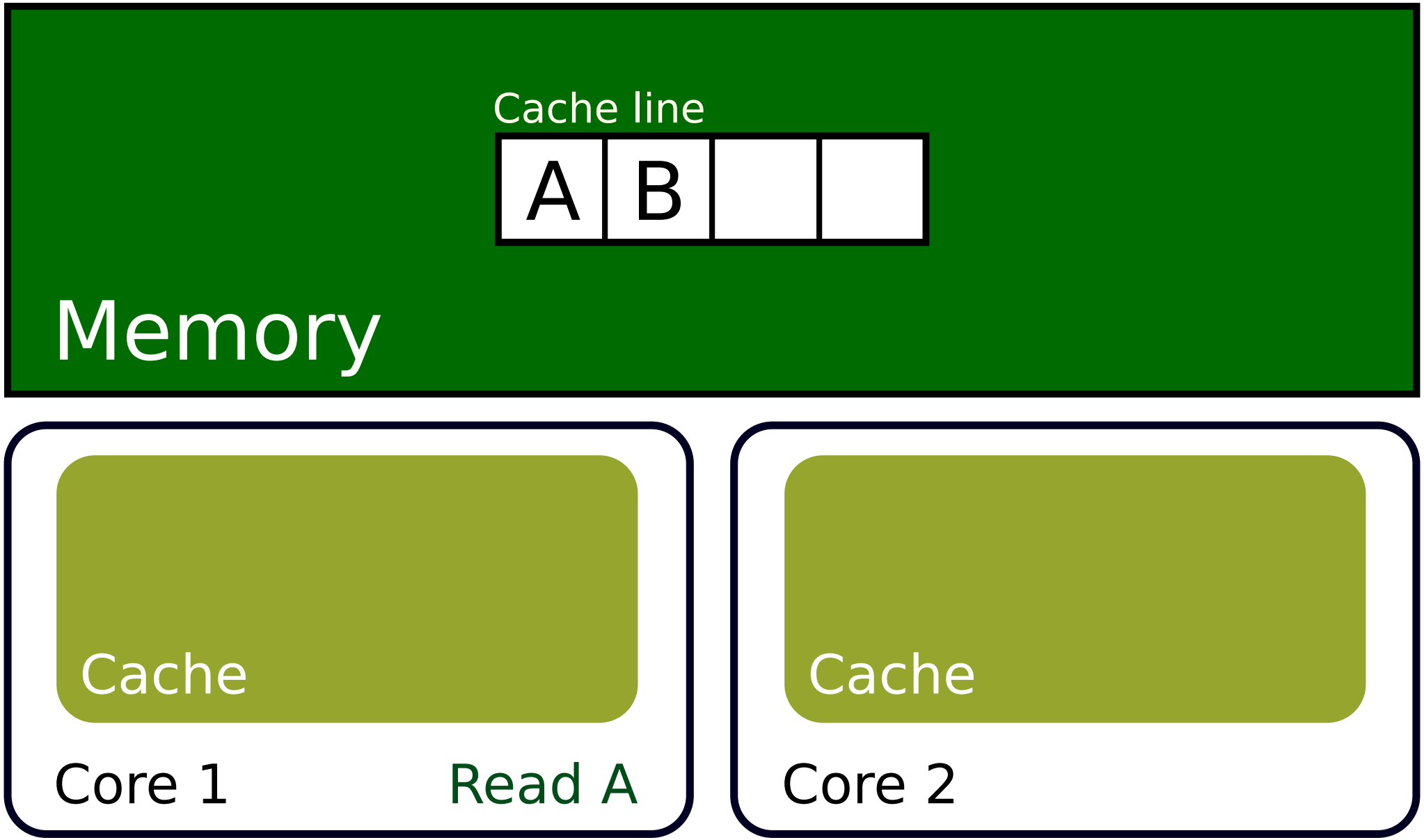
Cache system



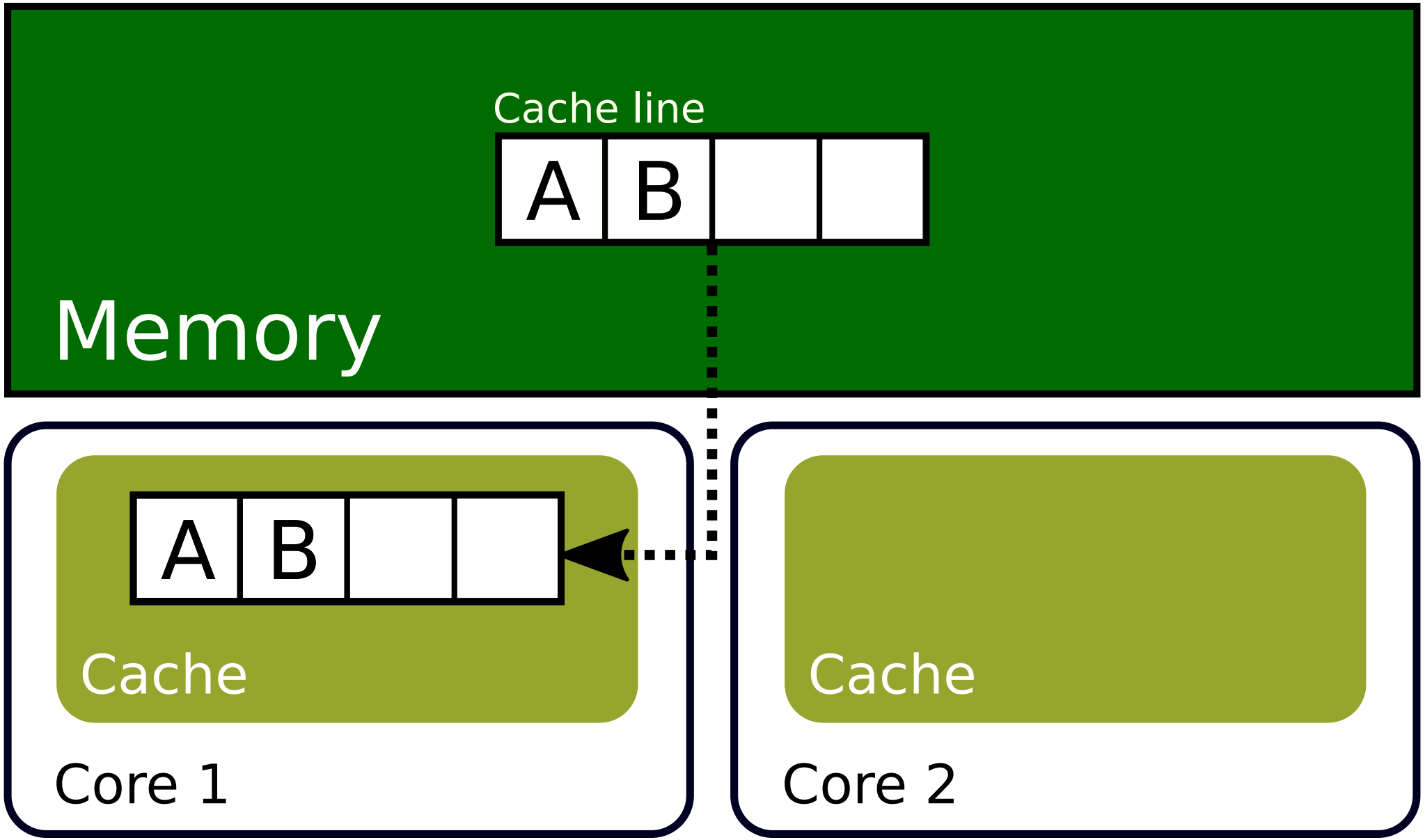
Cache coherency



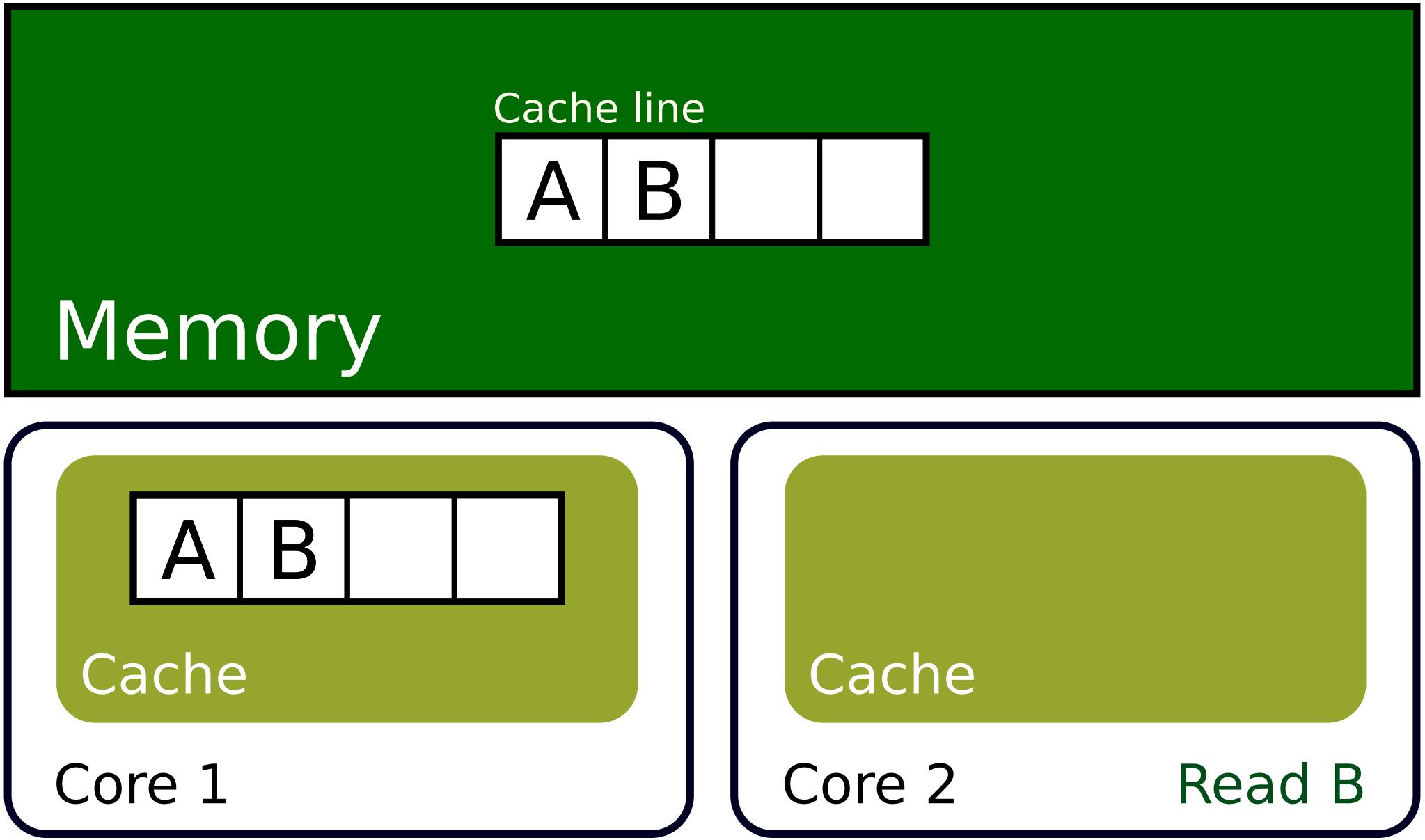
Cache coherency



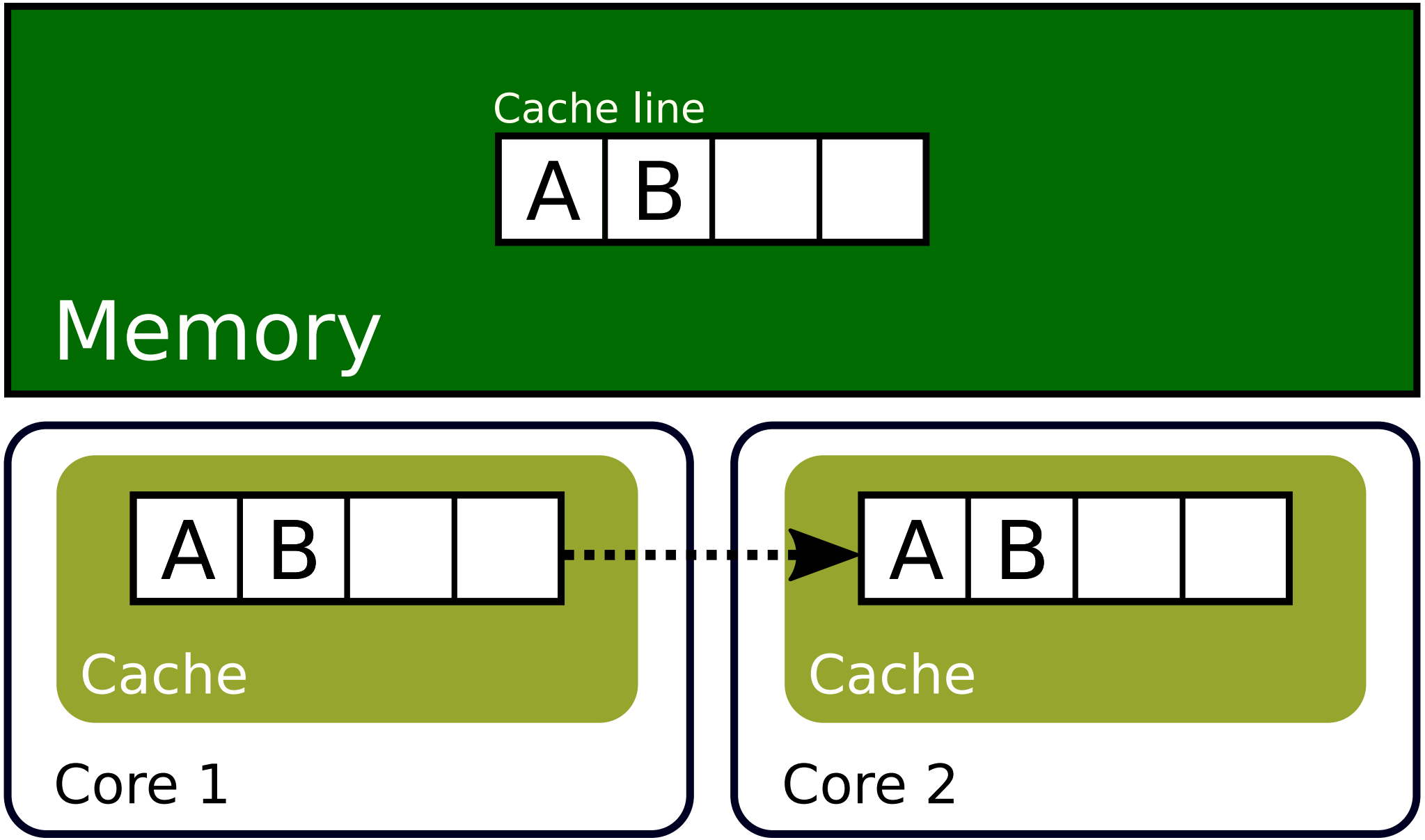
Cache coherency



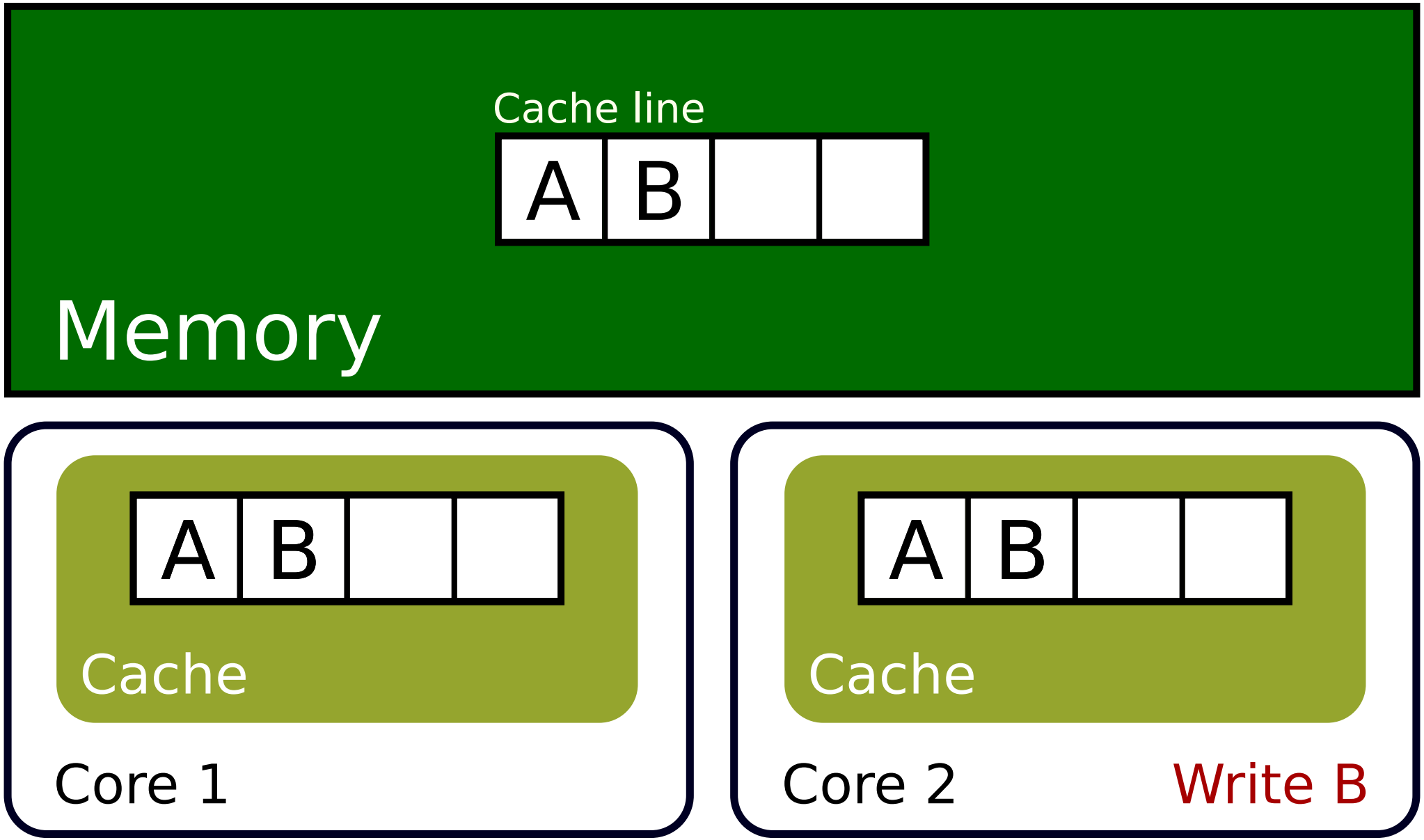
Cache coherency



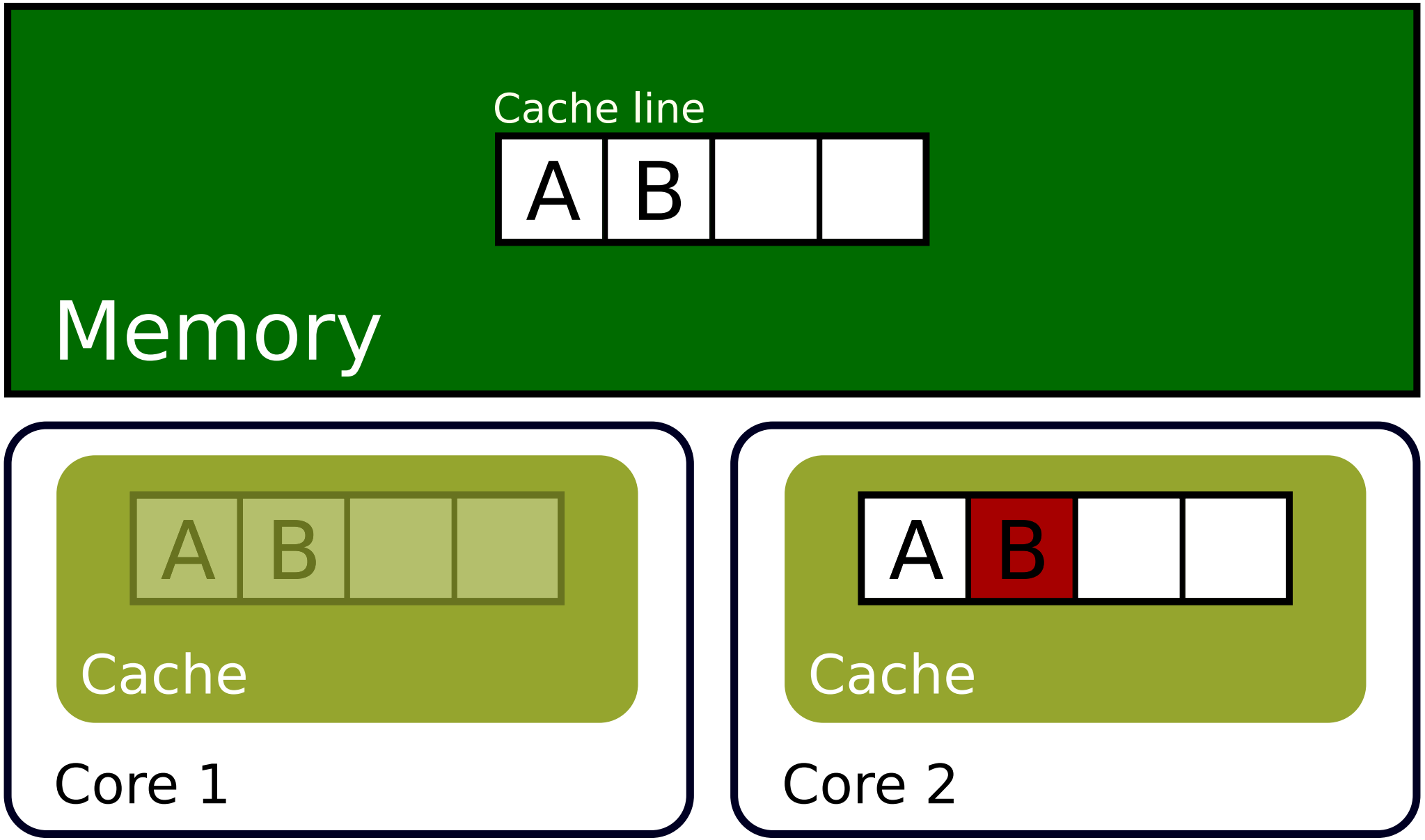
Cache coherency



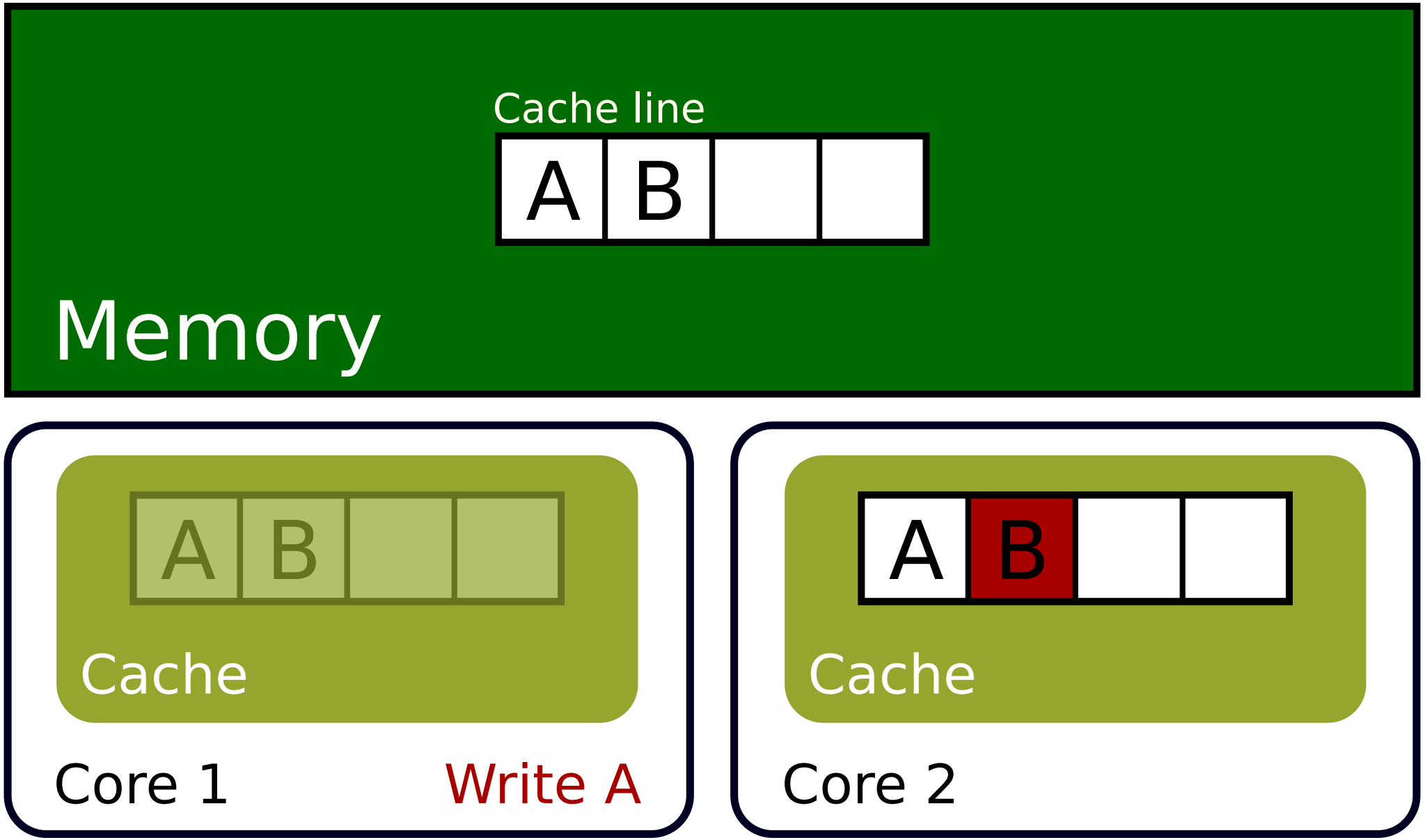
Cache coherency



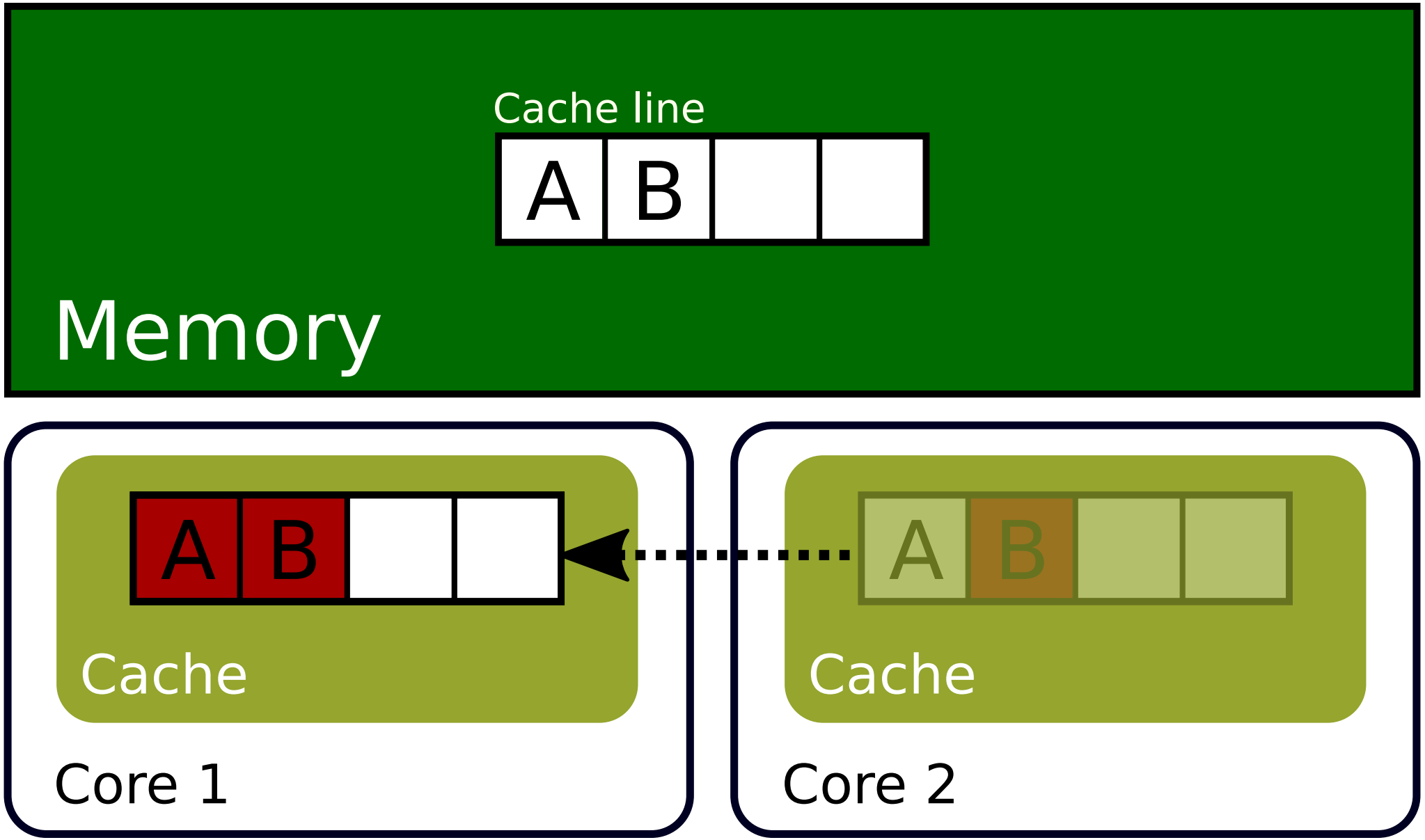
Cache coherency



Cache coherency

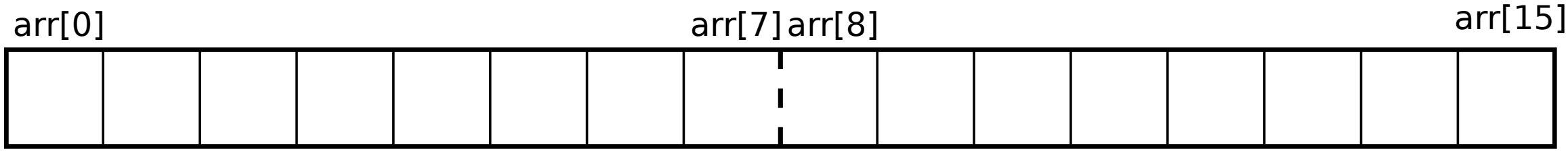


Cache coherency



False sharing

```
double arr[16];
```



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```
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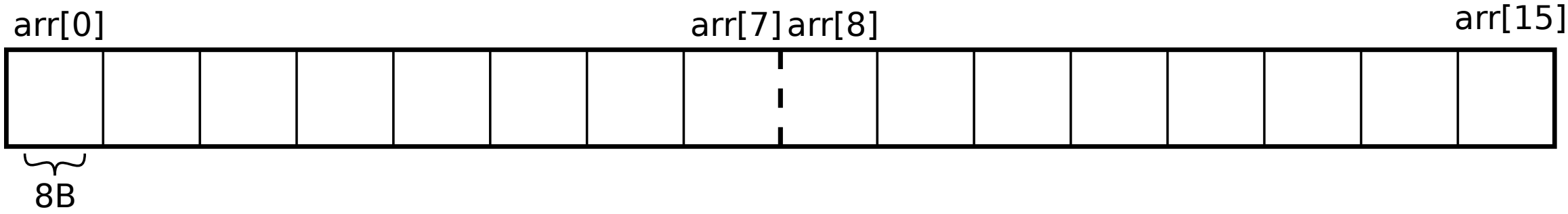
```



False sharing

```
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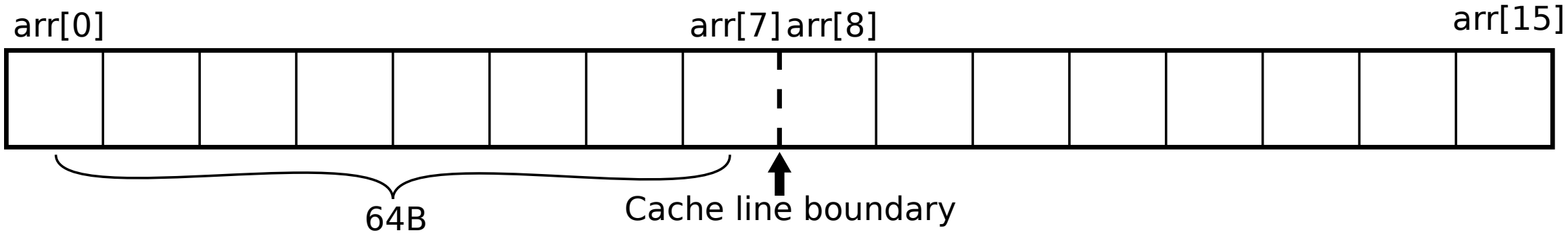

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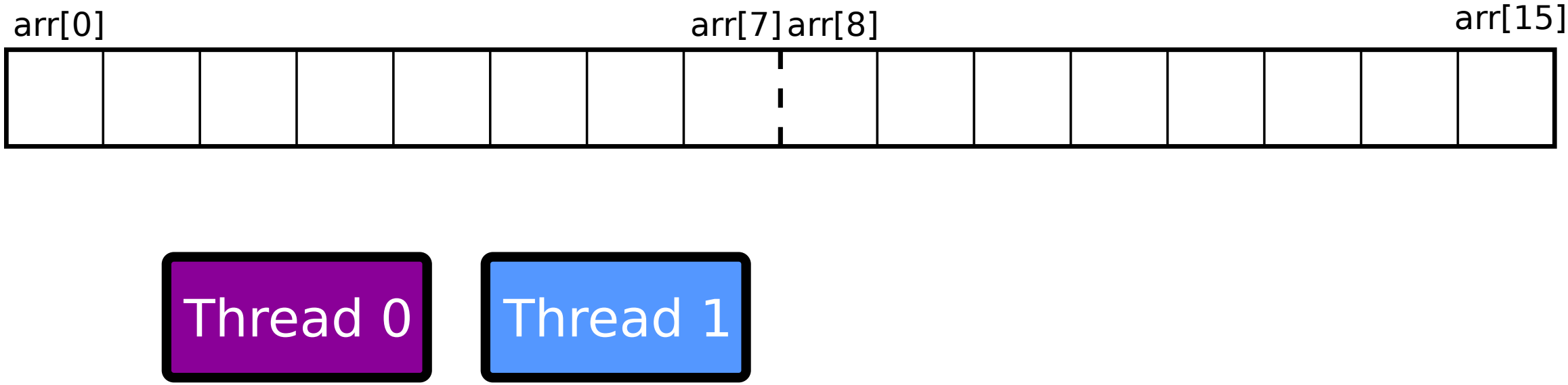

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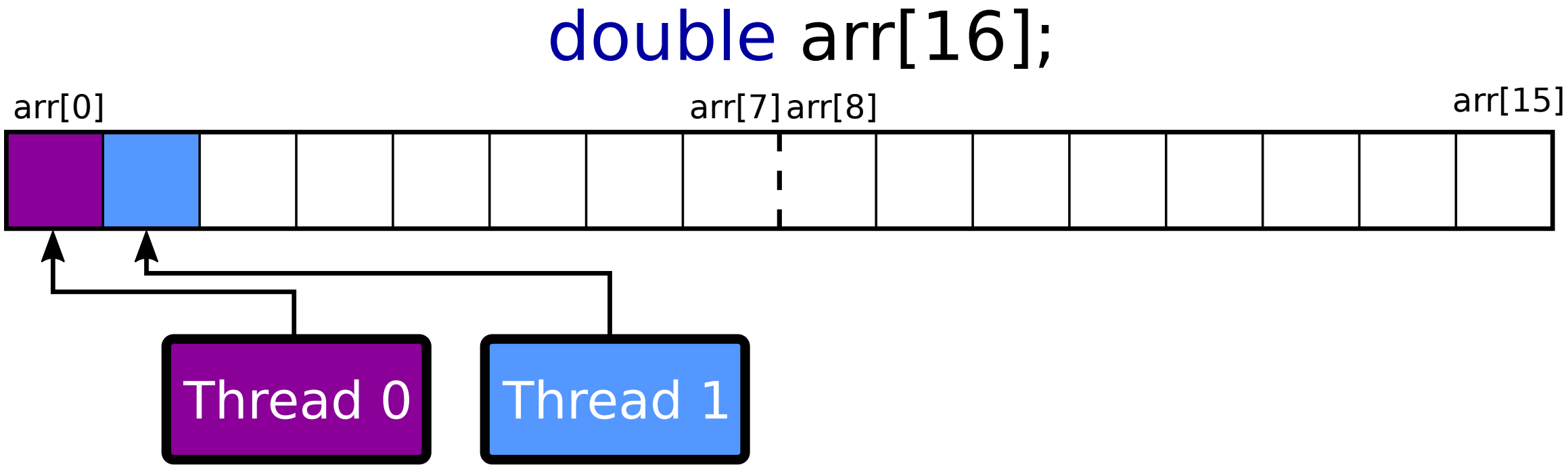

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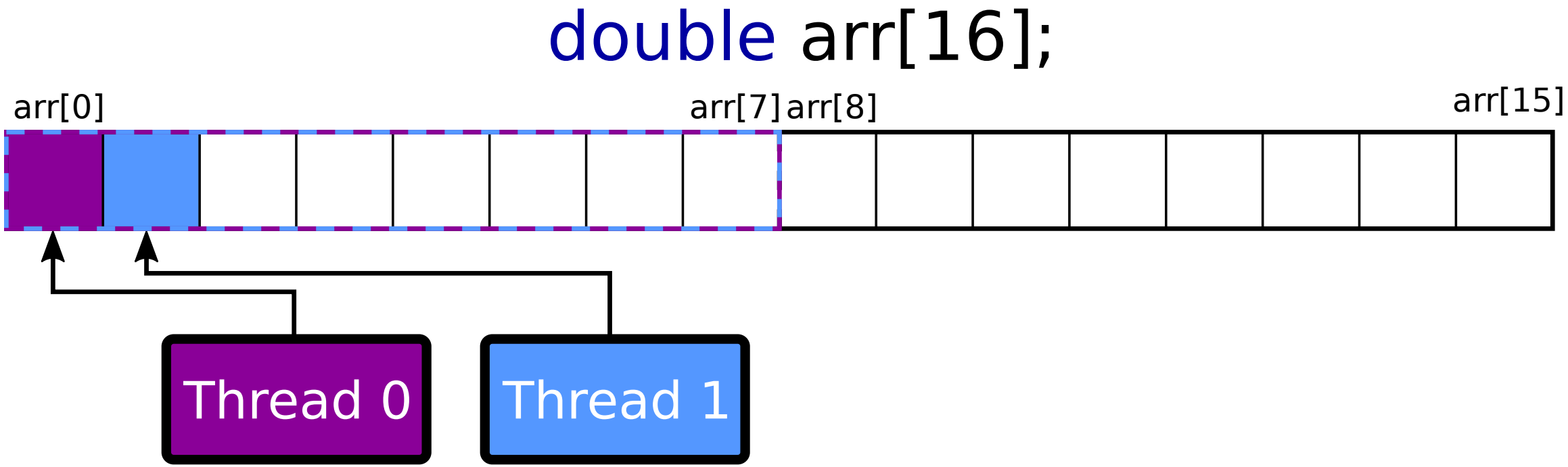

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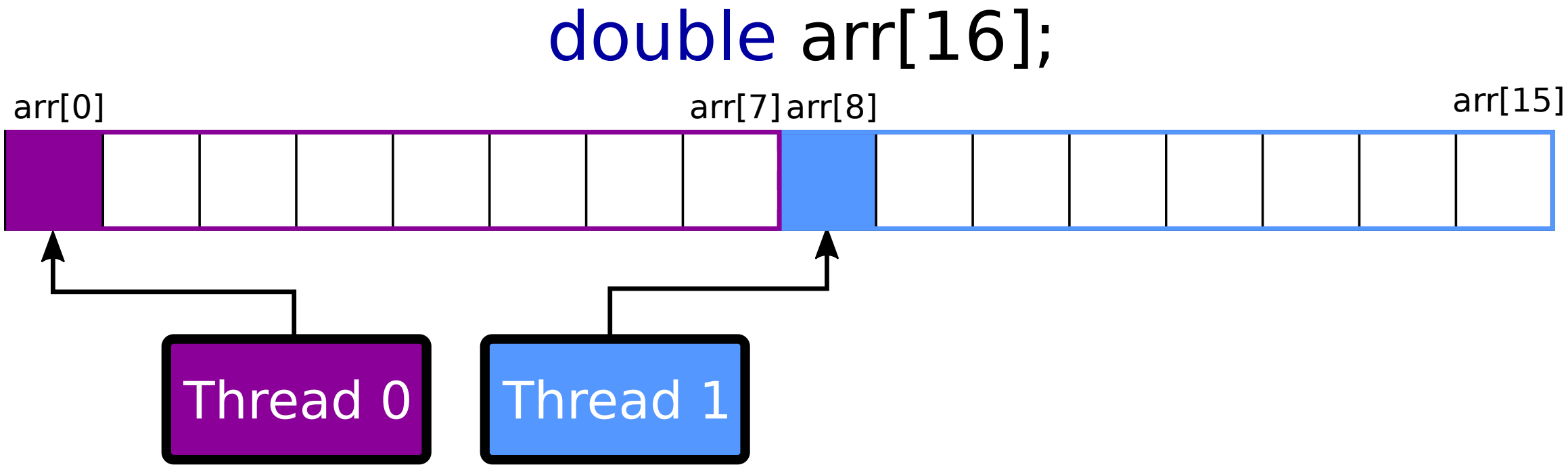

How to measure?

`l2_rqsts.all_rfo`

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```
$ perf stat -e l2_rqsts.all_rfo ./example3
1 thread   ->          59 711
2 threads  -> 1 112 258 710
```