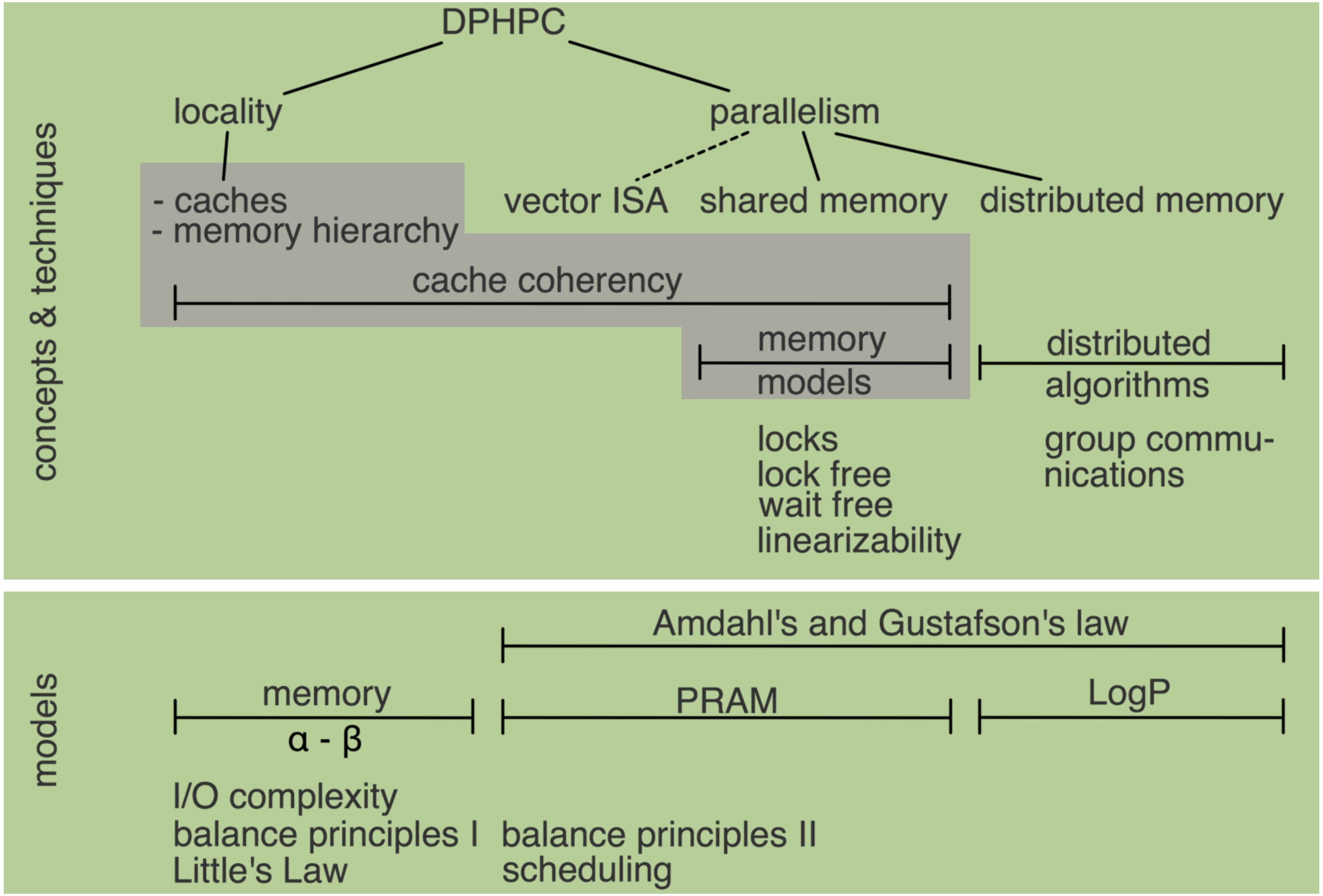
T. HOEFLER, M. PUESCHEL

Lecture 2: Caches and Cache Coherence

Teaching assistant: Salvatore Di Girolamo

Motivational video: *https://www.youtube.com/watch?v=zJybFF6PqEQ*

DPHPC Overview

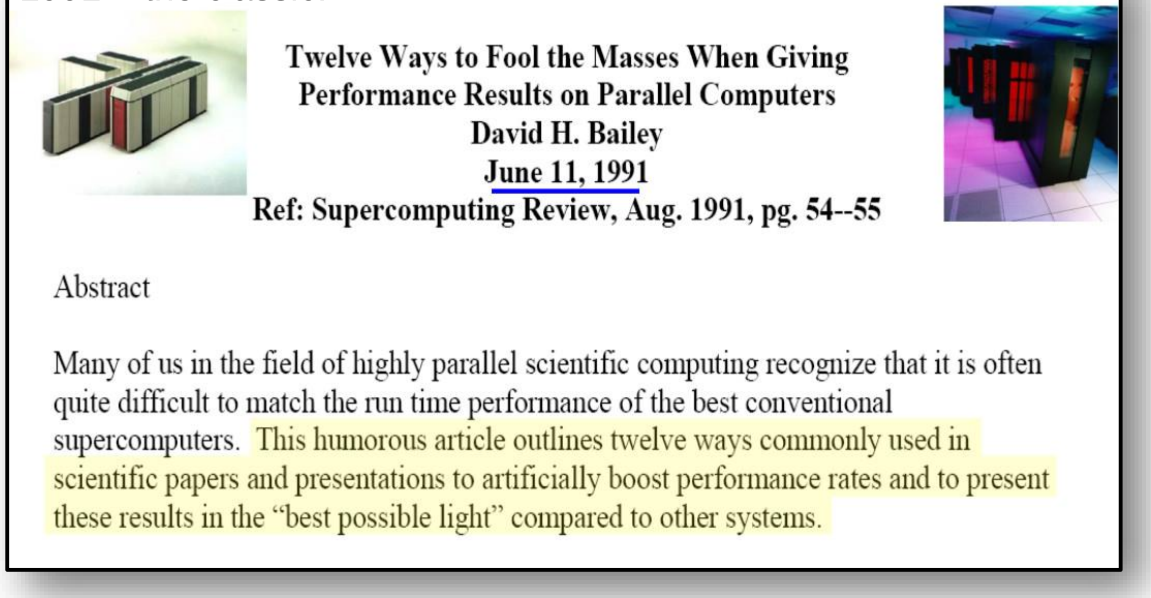


Scientific integrity – or how to report benchmark results?

TH, R. Belli: Scientific Benchmarking of Parallel Computing Systems, IEEE/ACM SC15 (full talk at https://www.youtube.com/watch?v=HwEpXIWAWTU)

Scientific integrity – or how to report benchmark results?

1991 – the classic!



Twelve Ways to Fool the Masses When Giving
Performance Results on Parallel Computers
David H. Bailey
June 11, 1991
Ref: Supercomputing Review, Aug. 1991, pg. 54--55

Abstract

Many of us in the field of highly parallel scientific computing recognize that it is often quite difficult to match the run time performance of the best conventional supercomputers. This humorous article outlines twelve ways commonly used in scientific papers and presentations to artificially boost performance rates and to present these results in the "best possible light" compared to other systems.

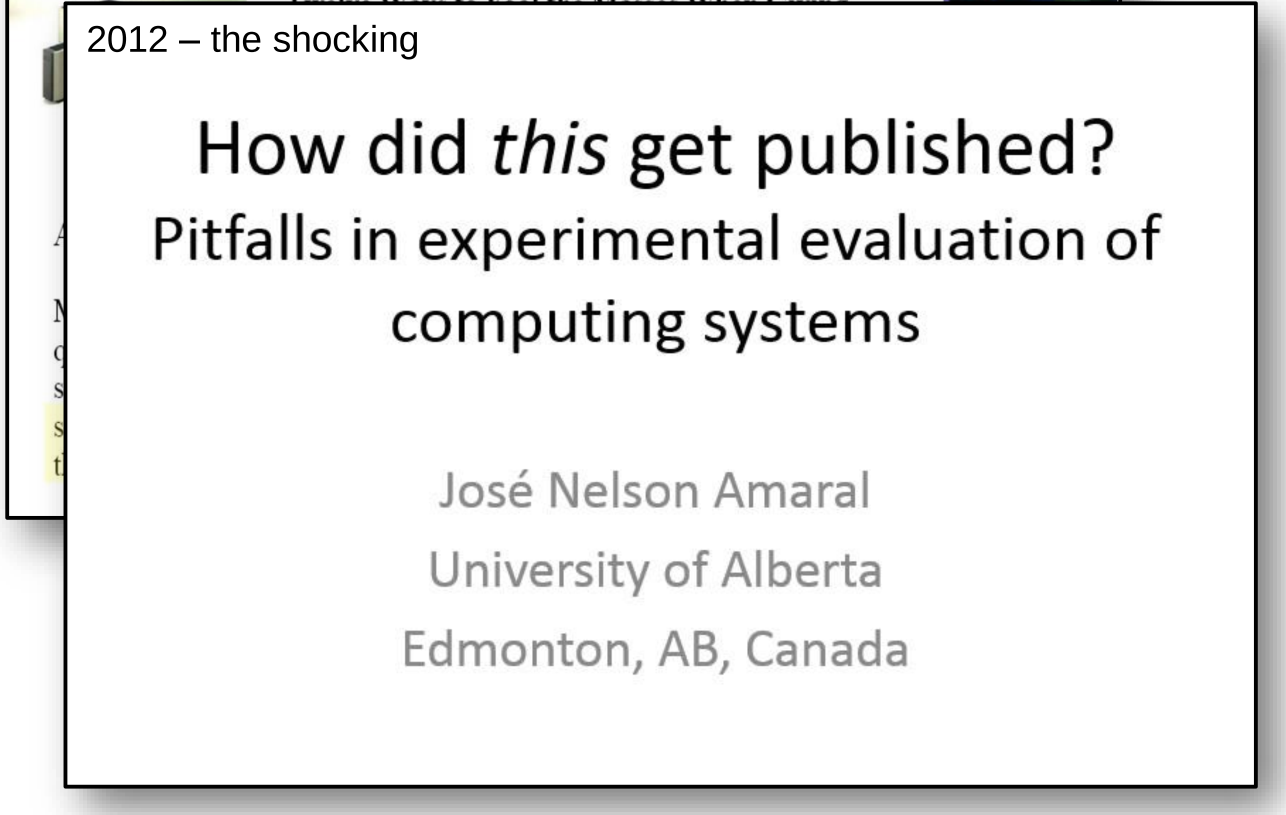
TH, R. Belli: Scientific Benchmarking of Parallel Computing Systems, IEEE/ACM SC15 (full talk at https://www.youtube.com/watch?v=HwEpXIWAWTU)

Scientific integrity – or how to report benchmark results?

1991 – the classic!

Twelve Ways to Fool the Masses When Giving

2012 – the shocking



How did *this* get published?

Pitfalls in experimental evaluation of computing systems

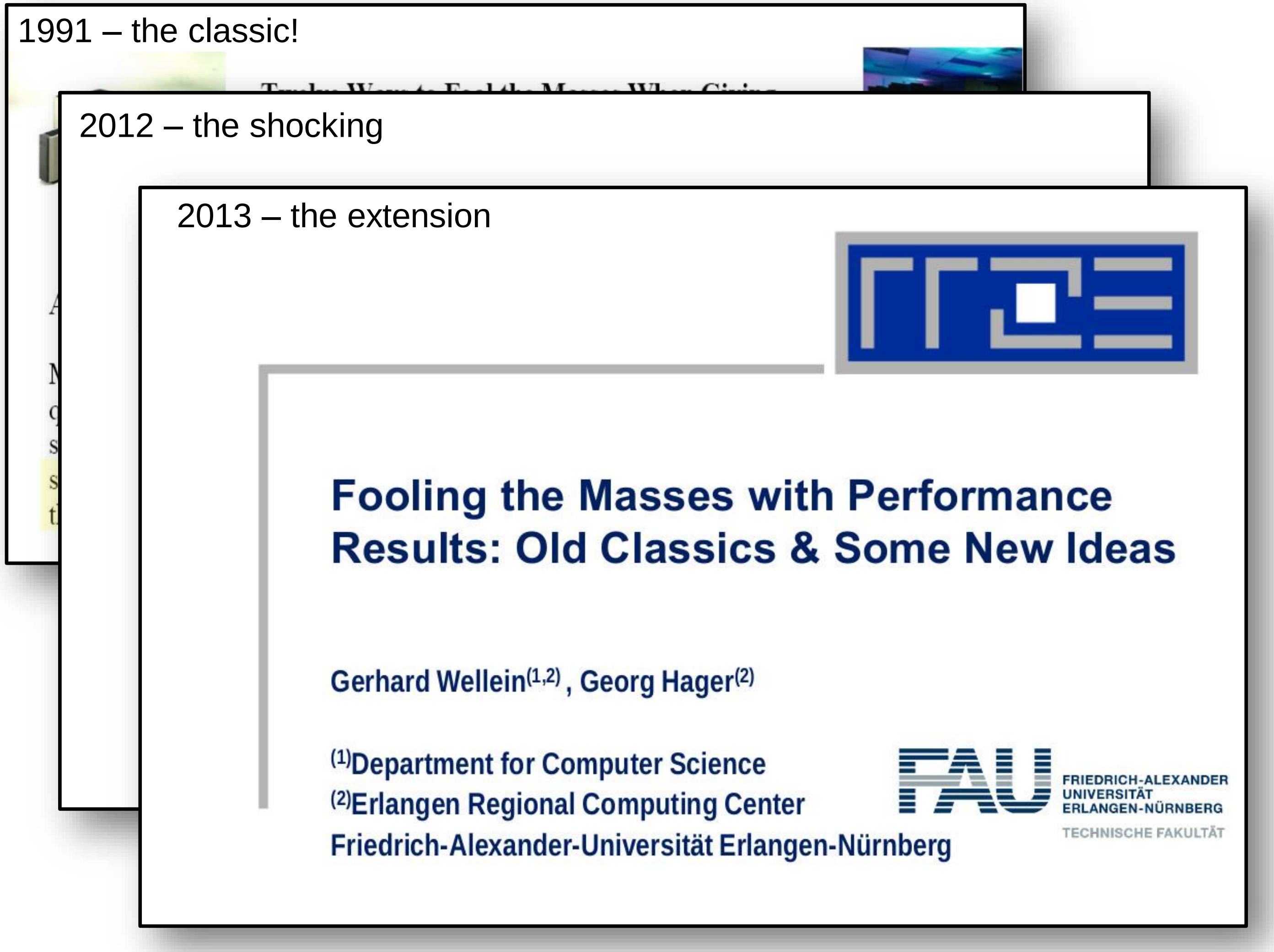
José Nelson Amaral

University of Alberta

Edmonton, AB, Canada

TH, R. Belli: Scientific Benchmarking of Parallel Computing Systems, IEEE/ACM SC15 (full talk at https://www.youtube.com/watch?v=HwEpXIWAWTU)

Scientific integrity – or how to report benchmark results?



1991 – the classic!

Twelve Ways to Fool the Masses When Giving

2012 – the shocking

2013 – the extension

Fooling the Masses with Performance Results: Old Classics & Some New Ideas

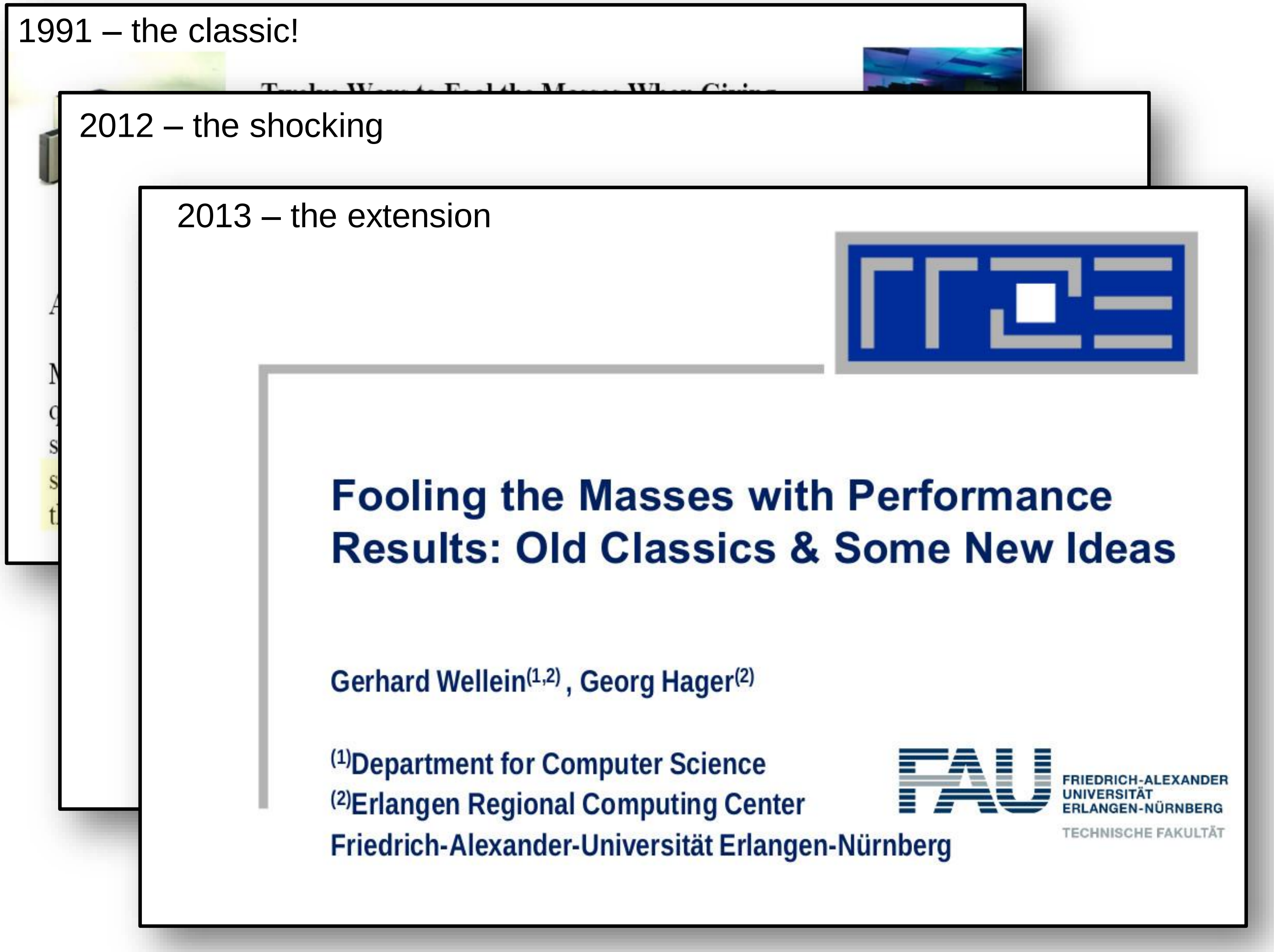
Gerhard Wellein[1,2] , Georg Hager[2]

[1]Department for Computer Science
[2]Erlangen Regional Computing Center
Friedrich-Alexander-Universität Erlangen-Nürnberg

…

TH, R. Belli: Scientific Benchmarking of Parallel Computing Systems, IEEE/ACM SC15 (full talk at https://www.youtube.com/watch?v=HwEpXIWAWTU)

Scientific integrity – or how to report benchmark results?



1991 – the classic!

Twelve Ways to Fool the Masses When Giving

2012 – the shocking

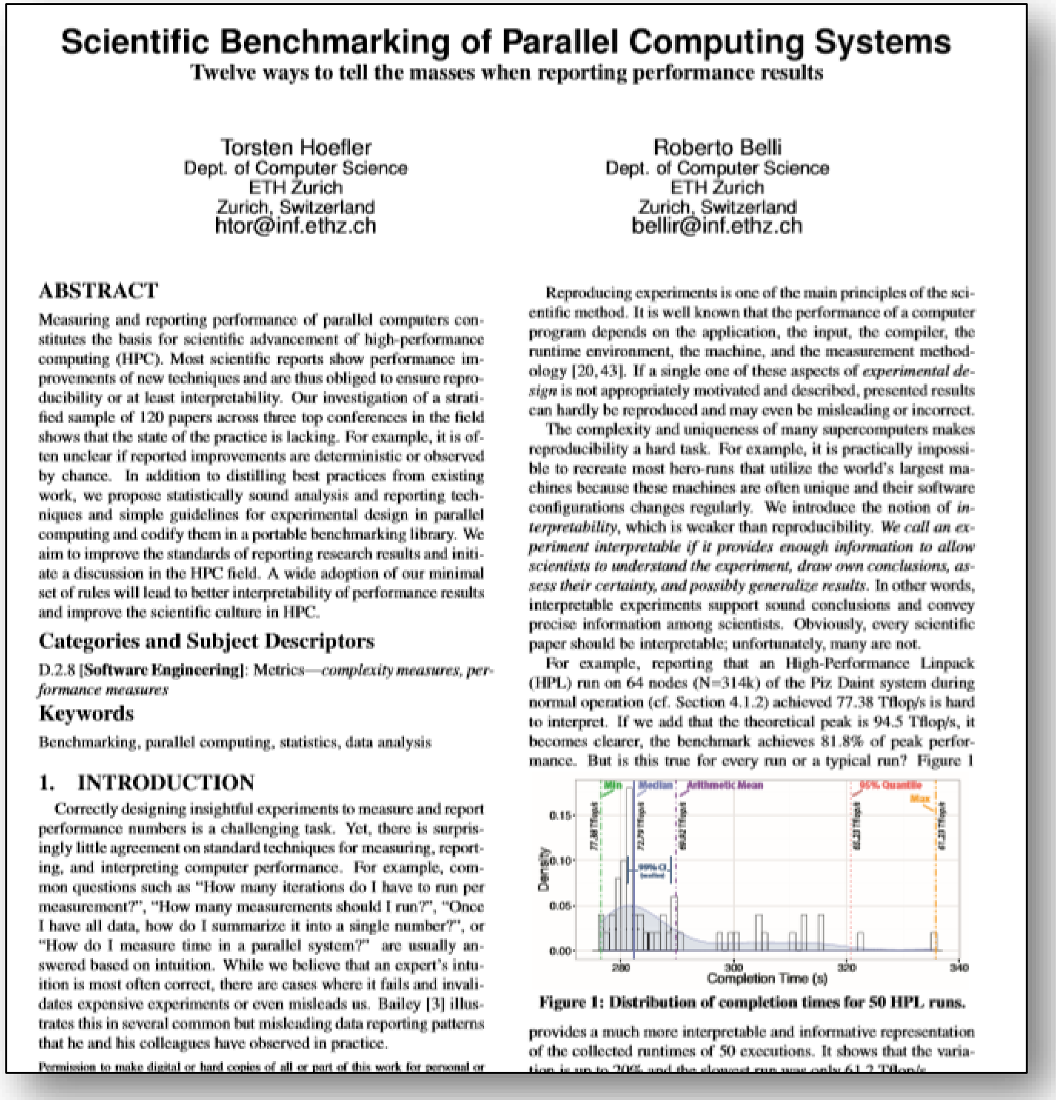
2013 – the extension

Fooling the Masses with Performance Results: Old Classics & Some New Ideas

Gerhard Wellein[1,2] , Georg Hager[2]

[1]Department for Computer Science
[2]Erlangen Regional Computing Center
Friedrich-Alexander-Universität Erlangen-Nürnberg

FRIEDRICH-ALEXANDER UNIVERSITÄT ERLANGEN-NÜRNBERG
TECHNISCHE FAKULTÄT



Scientific Benchmarking of Parallel Computing Systems
Twelve ways to tell the masses when reporting performance results

Torsten Hoefler
Dept. of Computer Science
ETH Zurich
Zurich, Switzerland
htor@inf.ethz.ch

Roberto Belli
Dept. of Computer Science
ETH Zurich
Zurich, Switzerland
bellir@inf.ethz.ch

ABSTRACT

Measuring and reporting performance of parallel computers constitutes the basis for scientific advancement of high-performance computing (HPC). Most scientific reports show performance improvements of new techniques and are thus obliged to ensure reproducibility or at least interpretability. Our investigation of a stratified sample of 120 papers across three top conferences in the field shows that the state of the practice is lacking. For example, it is often unclear if reported improvements are deterministic or observed by chance. In addition to distilling best practices from existing work, we propose statistically sound analysis and reporting techniques and simple guidelines for experimental design in parallel computing and codify them in a portable benchmarking library. We aim to improve the standards of reporting research results and initiate a discussion in the HPC field. A wide adoption of our minimal set of rules will lead to better interpretability of performance results and improve the scientific culture in HPC.

Categories and Subject Descriptors

D.2.8 [**Software Engineering**]: Metrics—*complexity measures, performance measures*

Keywords

Benchmarking, parallel computing, statistics, data analysis

1. INTRODUCTION

Correctly designing insightful experiments to measure and report performance numbers is a challenging task. Yet, there is surprisingly little agreement on standard techniques for measuring, reporting, and interpreting computer performance. For example, common questions such as "How many iterations do I have to run per measurement?", "How many measurements should I run?", "Once I have all data, how do I summarize it into a single number?", or "How do I measure time in a parallel system?" are usually answered based on intuition. While we believe that an expert's intuition is most often correct, there are cases where it fails and invalidates expensive experiments or even misleads us. Bailey [3] illustrates this in several common but misleading data reporting patterns that he and his colleagues have observed in practice.

Permission to make digital or hard copies of all or part of this work for personal or

Reproducing experiments is one of the main principles of the scientific method. It is well known that the performance of a computer program depends on the application, the input, the compiler, the runtime environment, the machine, and the measurement methodology [20, 43]. If a single one of these aspects of *experimental design* is not appropriately motivated and described, presented results can hardly be reproduced and may even be misleading or incorrect.

The complexity and uniqueness of many supercomputers makes reproducibility a hard task. For example, it is practically impossible to recreate most hero-runs that utilize the world's largest machines because these machines are often unique and their software configurations changes regularly. We introduce the notion of *interpretability*, which is weaker than reproducibility. *We call an experiment interpretable if it provides enough information to allow scientists to understand the experiment, draw own conclusions, assess their certainty, and possibly generalize results.* In other words, interpretable experiments support sound conclusions and convey precise information among scientists. Obviously, every scientific paper should be interpretable; unfortunately, many are not.

For example, reporting that an High-Performance Linpack (HPL) run on 64 nodes (N=314k) of the Piz Daint system during normal operation (cf. Section 4.1.2) achieved 77.38 Tflop/s is hard to interpret. If we add that the theoretical peak is 94.5 Tflop/s, it becomes clearer, the benchmark achieves 81.8% of peak performance. But is this true for every run or a typical run? Figure 1 provides a much more interpretable and informative representation of the collected runtimes of 50 executions. It shows that the variation is up to 20% and the slowest run was only 61.2 Tflop/s.

Figure 1: Distribution of completion times for 50 HPL runs.

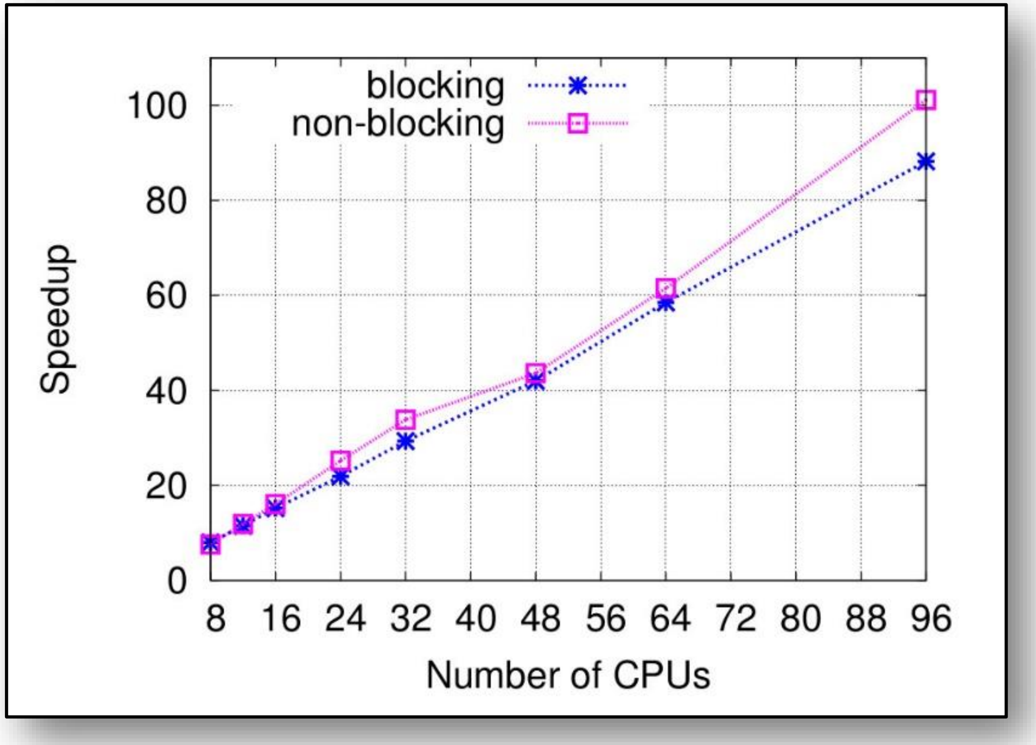
TH, R. Belli: Scientific Benchmarking of Parallel Computing Systems, IEEE/ACM SC15 (full talk at https://www.youtube.com/watch?v=HwEpXIWAWTU)

Scientific Benchmarking: Pitfalls of Relative Performance Reporting (Rule 1)

- **Most common (and oldest) problem with reporting**
  - First seen 1988 – also included in Bailey's 12 ways
  - Speedups can look arbitrarily good if it's relative to a bad baseline
  - Imagine an unoptimized vs. parallel matrix multiplication:

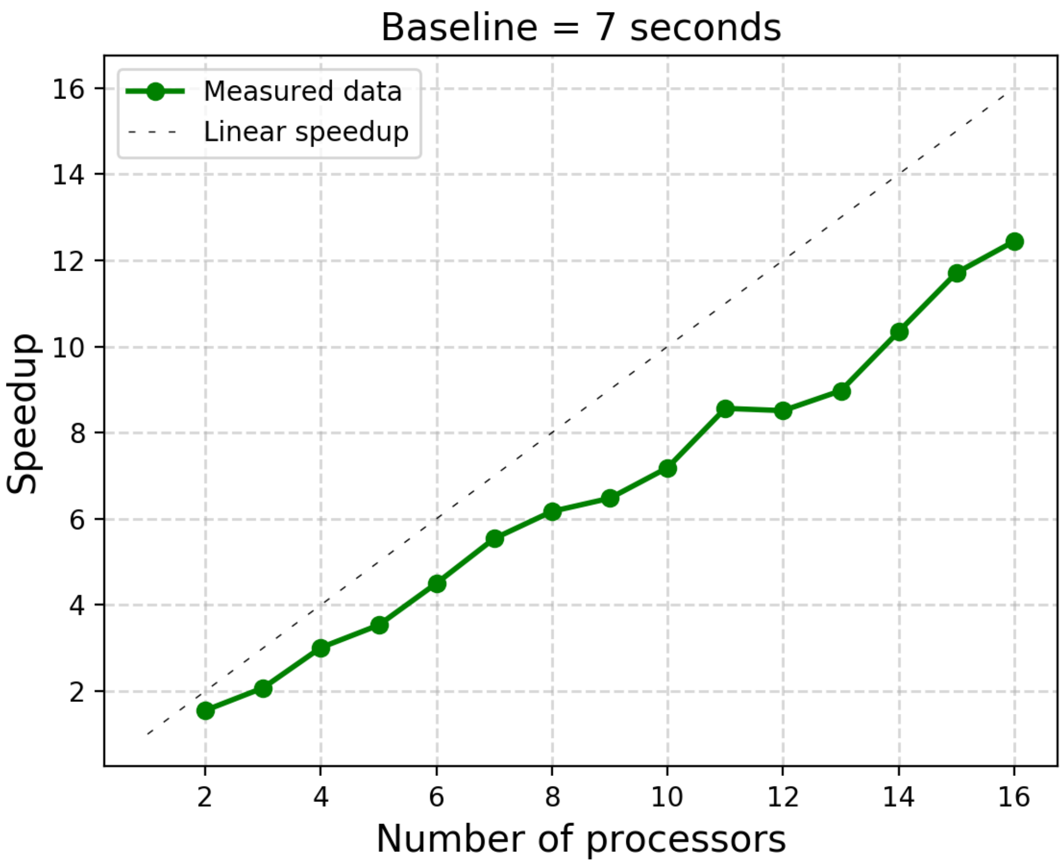
    My parallel MM is 10x faster than the unoptimized!

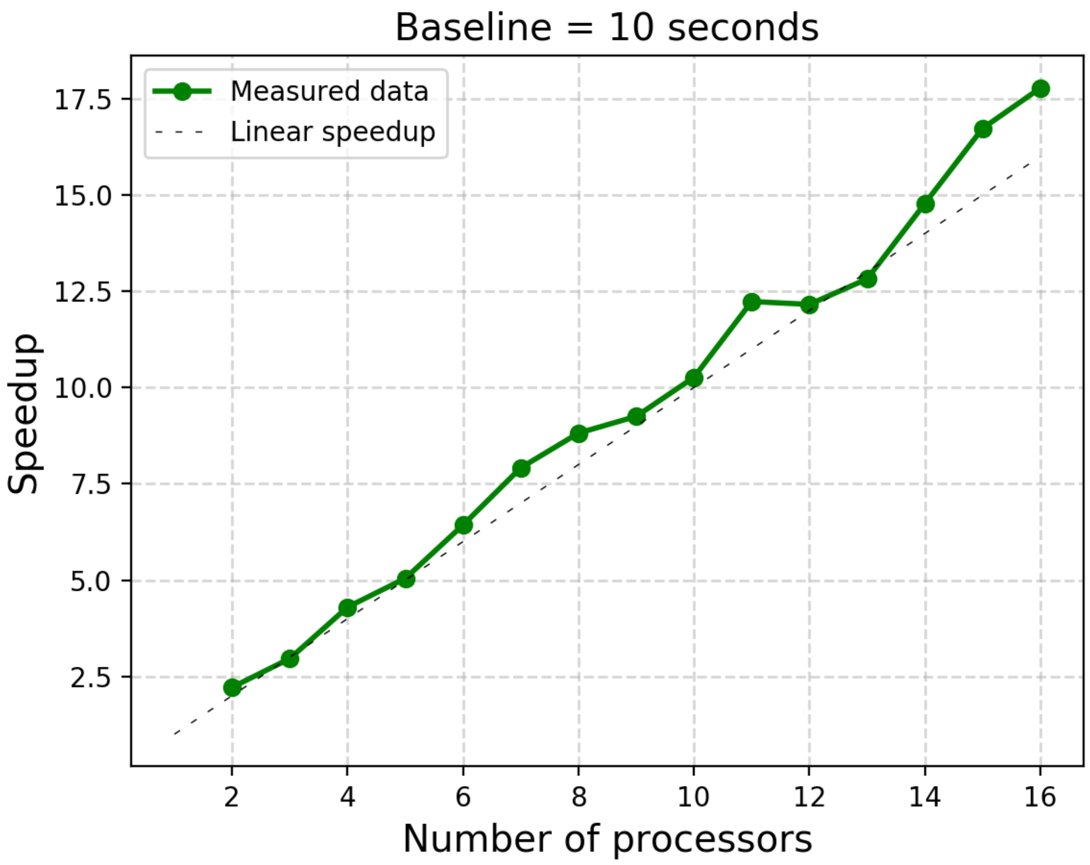
    What does this mean?



TH, R. Belli: Scientific Benchmarking of Parallel Computing Systems, IEEE/ACM SC15 (full talk at https://www.youtube.com/watch?v=HwEpXIWAWTU)

Scientific Benchmarking: Pitfalls of Relative Performance Reporting (Rule 1)





Both plots show speedups calculated from the same data.
The only difference is the baseline.

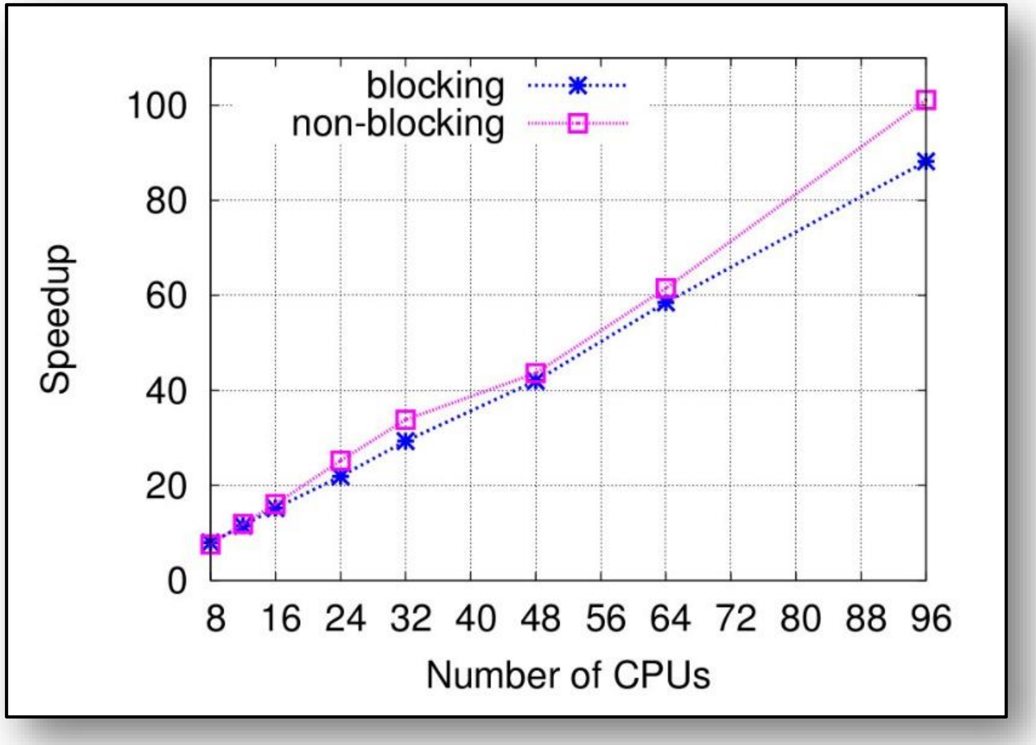
TH, R. Belli: Scientific Benchmarking of Parallel Computing Systems, IEEE/ACM SC15 (full talk at https://www.youtube.com/watch?v=HwEpXIWAWTU)

Scientific Benchmarking: Pitfalls of Relative Performance Reporting (Rule 1)

- **Most common (and oldest) problem with reporting**
  - First seen 1988 – also included in Bailey's 12 ways
  - Speedups can look arbitrarily good if it's relative to a bad baseline
  - Imagine an unoptimized vs. parallel matrix multiplication:

    My parallel MM is 10x faster than the unoptimized!

    What does this mean?



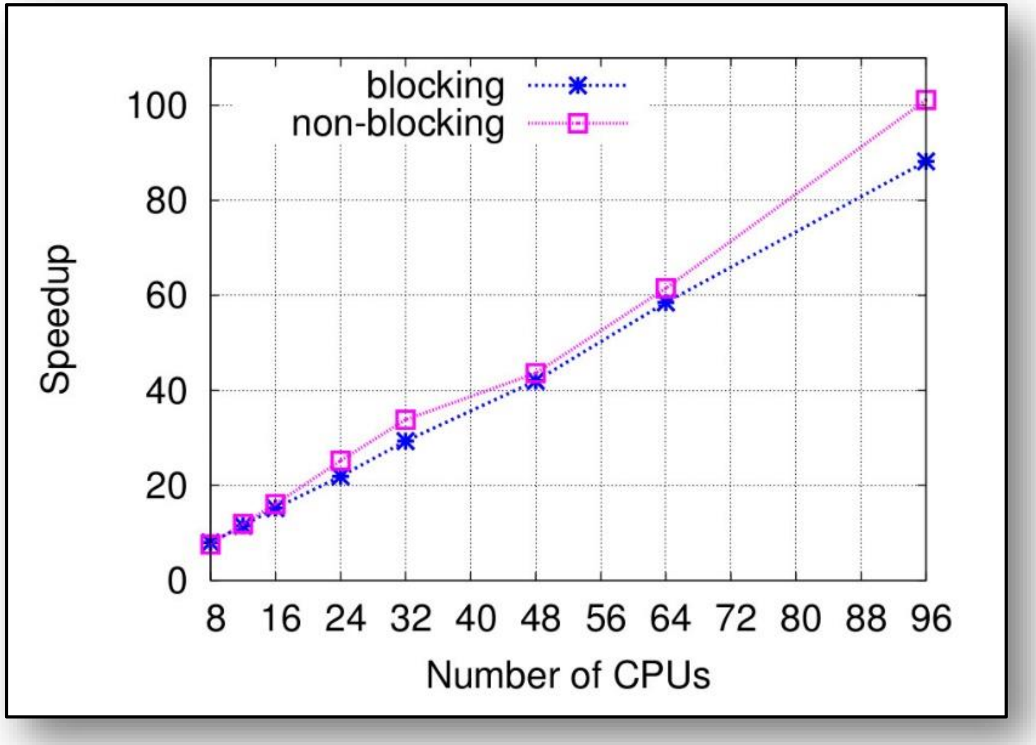
TH, R. Belli: Scientific Benchmarking of Parallel Computing Systems, IEEE/ACM SC15 (full talk at https://www.youtube.com/watch?v=HwEpXIWAWTU)

Scientific Benchmarking: Pitfalls of Relative Performance Reporting (Rule 1)

- **Most common (and oldest) problem with reporting**
  - First seen 1988 – also included in Bailey’s 12 ways
  - Speedups can look arbitrarily good if it’s relative to a bad baseline
  - Imagine an unoptimized vs. parallel matrix multiplication:

    My parallel MM is 10x faster than the unoptimized!

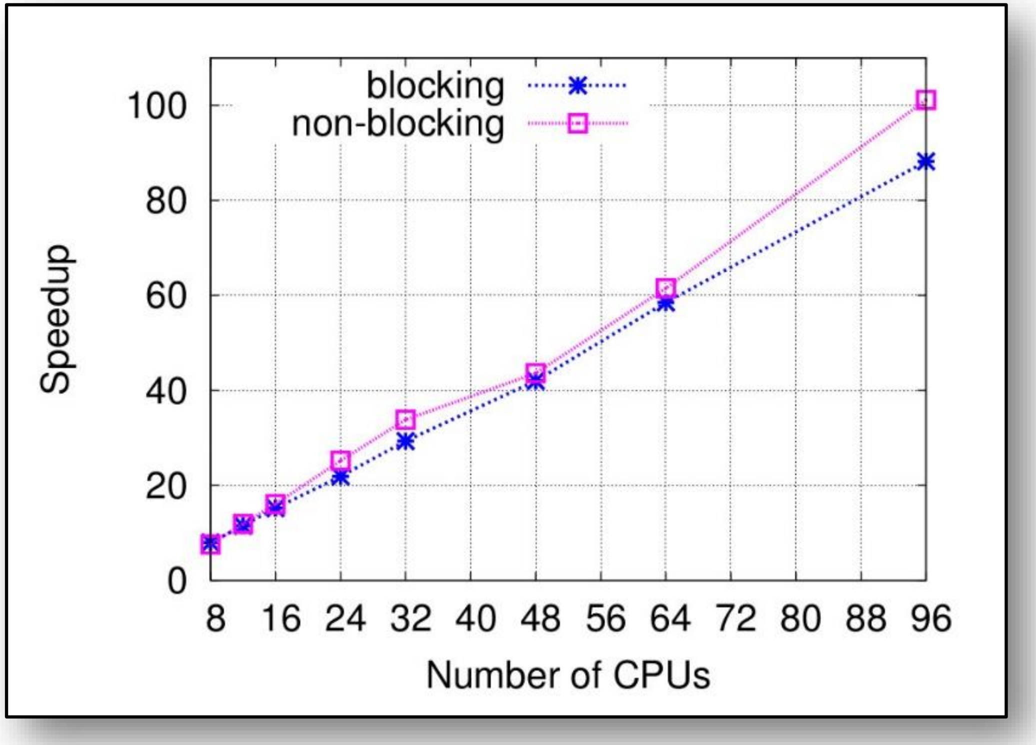
    What does this mean?
  - **Class question**: how could we improve the situation?



TH, R. Belli: Scientific Benchmarking of Parallel Computing Systems, IEEE/ACM SC15 (full talk at https://www.youtube.com/watch?v=HwEpXIWAWTU)

Scientific Benchmarking: Pitfalls of Relative Performance Reporting (Rule 1)

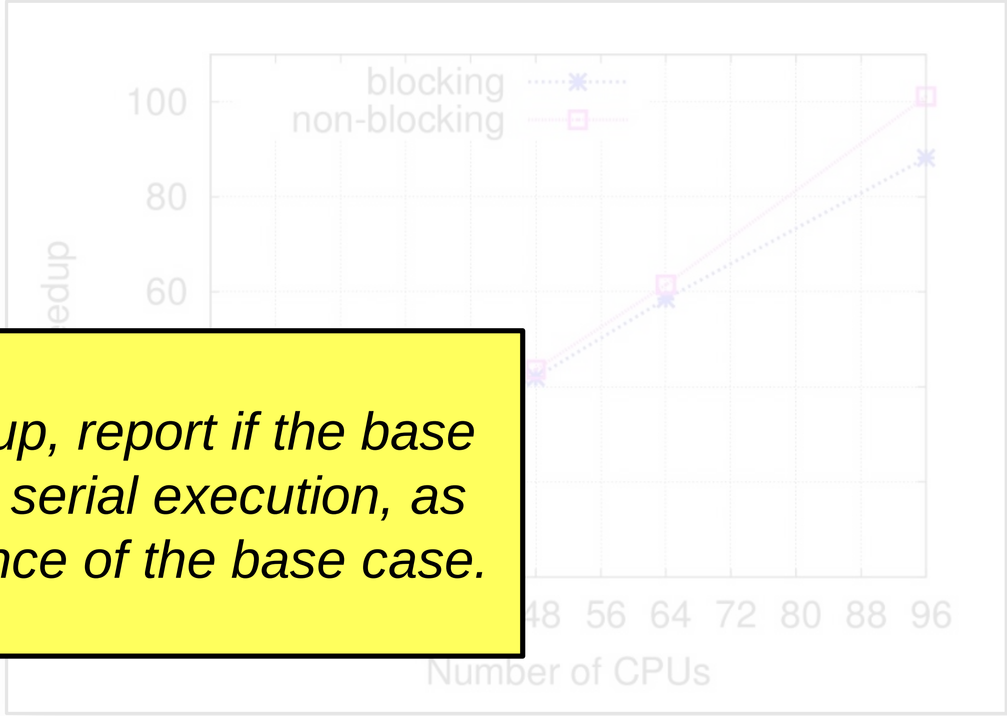
- **Most common (and oldest) problem with reporting**
  - First seen 1988 – also included in Bailey's 12 ways
  - Speedups can look arbitrarily good if it's relative to a bad baseline
  - Imagine an unoptimized vs. parallel matrix multiplication:
    My parallel MM is 10x faster than the unoptimized!
    What does this mean?
  - **Class question**: how could we improve the situation?
  - Recently rediscovered in the "big data" universe
    A. Rowstron et al.: Nobody ever got fired for using Hadoop on a cluster, HotCDP 2012
    F. McSherry et al.: Scalability! but at what cost?, HotOS 2015



TH, R. Belli: Scientific Benchmarking of Parallel Computing Systems, IEEE/ACM SC15 (full talk at https://www.youtube.com/watch?v=HwEpXIWAWTU)

Scientific Benchmarking: Pitfalls of Relative Performance Reporting (Rule 1)

- **Most common (and oldest) problem with reporting**
  - First seen 1988 – also included in Bailey's 12 ways
  - Speedups can look arbitrarily good if it's relative to a bad baseline
  - Imagine an unc
    The optimized I
    What does this



Rule 1: *When publishing parallel speedup, report if the base case is a single parallel process or best serial execution, as well as the absolute execution performance of the base case.*

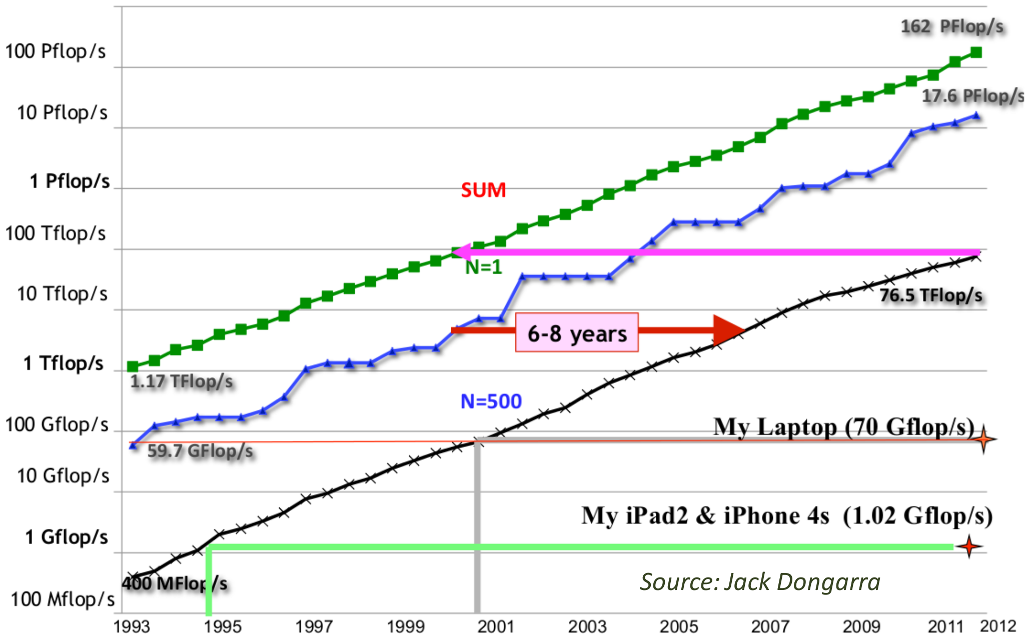
- **Class question**: how could we improve the situation?
  - **A simple generalization of this rule implies that one should never report ratios without absolute values.**
- Recently rediscovered in the "big data" universe
  A. Rowstron et al.: Nobody ever got fired for using Hadoop on a cluster, HotCDP 2012
  F. McSherry et al.: Scalability! but at what cost?, HotOS 2015

Goals of this lecture

- Memory Trends – Short Refresher on Locality and Caches!
- Cache Coherence in Multiprocessors
- Advanced Memory Consistency

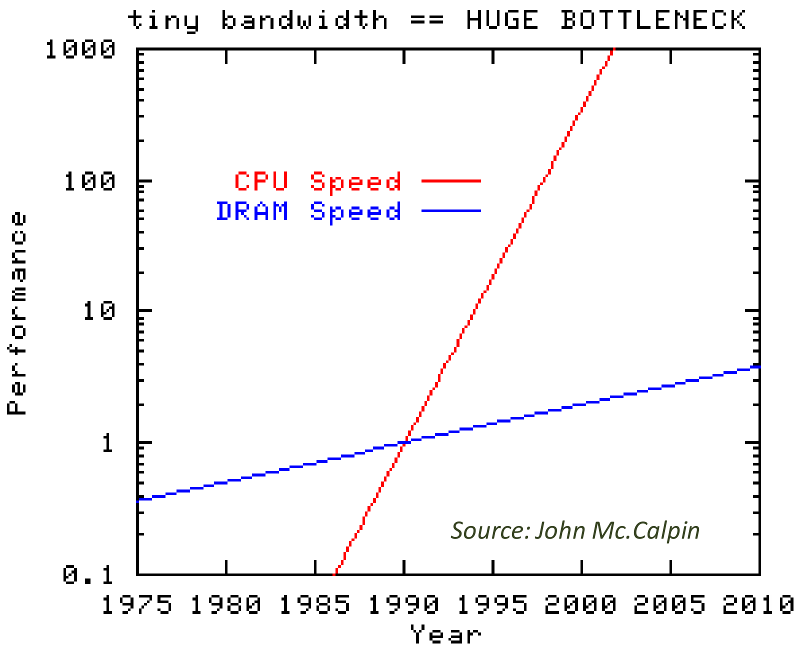
Memory – CPU gap widens

- **Measure processor speed as "throughput"**
  - FLOPS/s, IOPS/s, …
  - Moore's law - ~60% growth per year



Source: Jack Dongarra

- **Today's architectures**
  - POWER8: 425 dp GFLOP/s – 340 GB/s memory bw
  - Intel E5-2630 v4: 496 dp GFLOPS/s ~140 GB/s memory bw
  - Trend: memory performance grows 10% per year



Source: John Mc.Calpin

Issues (Intel Xeon E5-2630 v4 as Example)

- **How to measure bandwidth?**

Issues (Intel Xeon E5-2630 v4 as Example)

- **How to measure bandwidth?**
  - Data sheet (often peak performance, may include overheads)
    63.6 GiB/s

Issues (Intel Xeon E5-2630 v4 as Example)

- **How to measure bandwidth?**
  - Data sheet (often peak performance, may include overheads)

    63.6 GiB/s
  - Microbenchmark performance

    Stride 1 access (32 MiB): 46 GiB/s

    Random access (8 B out of 32 MiB): 4.7 GiB/s

    Why?

Issues (Intel Xeon E5-2630 v4 as Example)

- **How to measure bandwidth?**
  - Data sheet (often peak performance, may include overheads)

    63.6 GiB/s
  - Microbenchmark performance

    Stride 1 access (32 MiB): 46 GiB/s

    Random access (8 B out of 32 MiB): 4.7 GiB/s

    Why?
  - Application performance

    As observed (performance counters)

    Somewhere in between stride 1 and random access

Issues (Intel Xeon E5-2630 v4 as Example)

- **How to measure bandwidth?**
  - Data sheet (often peak performance, may include overheads)

    63.6 GiB/s
  - Microbenchmark performance

    Stride 1 access (32 MiB): 46 GiB/s

    Random access (8 B out of 32 MiB): 4.7 GiB/s

    Why?
  - Application performance

    As observed (performance counters)

    Somewhere in between stride 1 and random access
- **How to measure Latency?**

Issues (Intel Xeon E5-2630 v4 as Example)

- **How to measure bandwidth?**
  - Data sheet (often peak performance, may include overheads)

    63.6 GiB/s
  - Microbenchmark performance

    Stride 1 access (32 MiB): 46 GiB/s

    Random access (8 B out of 32 MiB): 4.7 GiB/s

    Why?
  - Application performance

    As observed (performance counters)

    Somewhere in between stride 1 and random access
- **How to measure Latency?**
  - Data sheet (often optimistic, or not provided)

Issues (Intel Xeon E5-2630 v4 as Example)

- **How to measure bandwidth?**
  - Data sheet (often peak performance, may include overheads)
    63.6 GiB/s
  - Microbenchmark performance
    Stride 1 access (32 MiB): 46 GiB/s
    Random access (8 B out of 32 MiB): 4.7 GiB/s
    Why?
  - Application performance
    As observed (performance counters)
    Somewhere in between stride 1 and random access
- **How to measure Latency?**
  - Data sheet (often optimistic, or not provided)
  - Random pointer chase
    28 ns with one core, 75 ns with 10 cores!

Conjecture: Buffering/caching is a must!

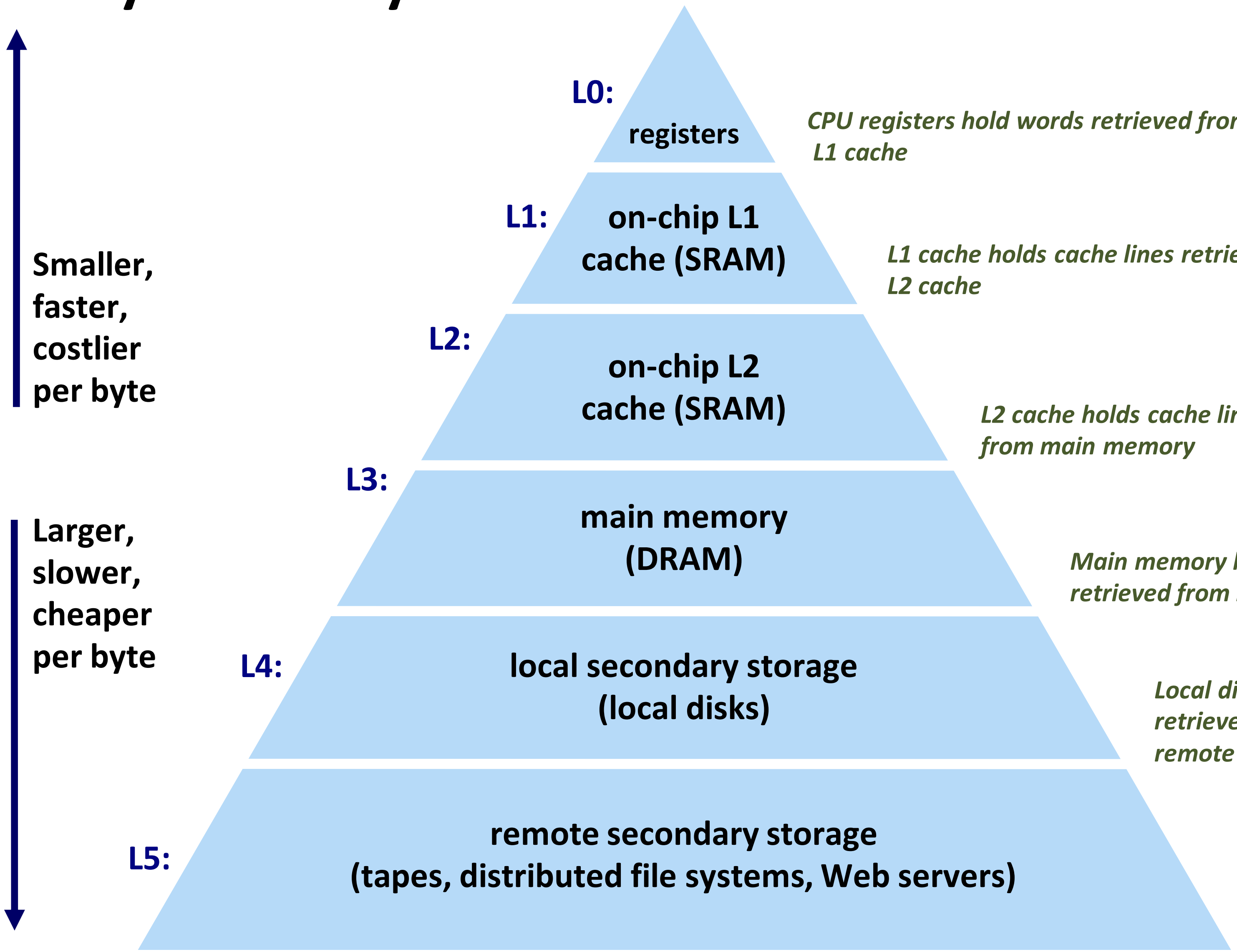
- **Two most common examples:**

- **Write Buffers**
  - Delayed write back saves memory bandwidth
  - Data is often overwritten or re-read

- **Caching**
  - Directory of recently used locations
  - Stored as blocks (cache lines)

- **Many others deep in architectures:**
  - Translation Lookahead Buffer
  - Branch Predictors
  - Trace Caches
  - …

Typical Memory Hierarchy


Smaller, faster, costlier per byte
Larger, slower, cheaper per byte
L0:
registers
L1:
on-chip L1 cache (SRAM)
L2:
on-chip L2 cache (SRAM)
L3:
main memory (DRAM)
L4:
local secondary storage (local disks)
L5:
remote secondary storage (tapes, distributed file systems, Web servers)

CPU registers hold words retrieved from L1 cache

L1 cache holds cache lines retrieved from L2 cache

L2 cache holds cache lines retrieved from main memory

Main memory holds disk blocks retrieved from local disks

Local disks hold files retrieved from disks on remote network servers

Why Caches Work: Locality

Why Caches Work: Locality

- *Locality:* **Programs tend to use data and instructions with addresses near or equal to those they have used recently, cf. "Denning: "The locality principle", CACM'05**

Why Caches Work: Locality

- *Locality:* **Programs tend to use data and instructions with addresses near or equal to those they have used recently, cf. "Denning: "The locality principle", CACM'05**

- *Temporal locality:*

Why Caches Work: Locality

- ***Locality:*** **Programs tend to use data and instructions with addresses near or equal to those they have used recently, cf. "Denning: "The locality principle", CACM'05**

- ***Temporal locality:***

  Recently referenced items are likely
  to be referenced again in the near future

Why Caches Work: Locality

- ***Locality:*** **Programs tend to use data and instructions with addresses near or equal to those they have used recently, cf. "Denning: "The locality principle", CACM'05**

- ***Temporal locality:***

  Recently referenced items are likely
  to be referenced again in the near future

- ***Spatial locality:***

Why Caches Work: Locality

- ***Locality:*** **Programs tend to use data and instructions with addresses near or equal to those they have used recently, cf. "Denning: "The locality principle", CACM'05**

- ***Temporal locality:***

  Recently referenced items are likely
  to be referenced again in the near future

- ***Spatial locality:***

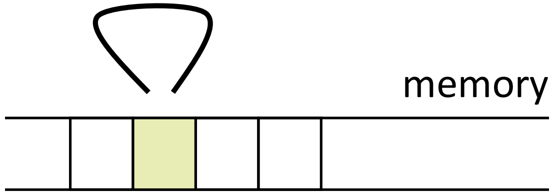
  Items with nearby addresses tend
  to be referenced close together in time

Why Caches Work: Locality

- ***Locality:*** **Programs tend to use data and instructions with addresses near or equal to those they have used recently, cf. "Denning: "The locality principle", CACM'05**

- ***Temporal locality:***

  Recently referenced items are likely
  to be referenced again in the near future



- ***Spatial locality:***

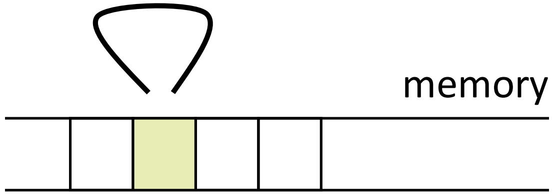
  Items with nearby addresses tend
  to be referenced close together in time

Why Caches Work: Locality

- *Locality:* **Programs tend to use data and instructions with addresses near or equal to those they have used recently, cf. "Denning: "The locality principle", CACM'05**

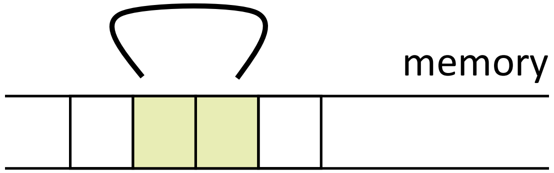
- *Temporal locality:*

  Recently referenced items are likely
  to be referenced again in the near future



- *Spatial locality:*

  Items with nearby addresses tend
  to be referenced close together in time



Example: Locality?

```
sum = 0;
for (i = 0; i < n; i++)
  sum += a[i];
return sum;
```

Example: Locality?

- **Data:**

```
sum = 0;
for (i = 0; i < n; i++)
  sum += a[i];
return sum;
```

Example: Locality?

- **Data:**
  - Temporal: **`sum`** referenced in each iteration

```
sum = 0;
for (i = 0; i < n; i++)
  sum += a[i];
return sum;
```

Example: Locality?

- **Data:**
  - Temporal: **`sum`** referenced in each iteration
  - Spatial: array **`a[]`** accessed consecutively

```
sum = 0;
for (i = 0; i < n; i++)
  sum += a[i];
return sum;
```

Example: Locality?

- **Data:**
  - Temporal: **sum** referenced in each iteration
  - Spatial: array **a[]** accessed consecutively

```
sum = 0;
for (i = 0; i < n; i++)
  sum += a[i];
return sum;
```

- **Instructions:**

Example: Locality?

- **Data:**
  - Temporal: **sum** referenced in each iteration
  - Spatial: array **a[]** accessed consecutively

- **Instructions:**
  - Temporal: loops cycle through the same instructions

```
sum = 0;
for (i = 0; i < n; i++)
  sum += a[i];
return sum;
```

Example: Locality?

- **Data:**
  - Temporal: **sum** referenced in each iteration
  - Spatial: array **a[]** accessed consecutively

- **Instructions:**
  - Temporal: loops cycle through the same instructions
  - Spatial: instructions referenced in sequence

```
sum = 0;
for (i = 0; i < n; i++)
  sum += a[i];
return sum;
```

Example: Locality?

```
sum = 0;
for (i = 0; i < n; i++)
  sum += a[i];
return sum;
```

- **Data:**
  - Temporal: **sum** referenced in each iteration
  - Spatial: array **a[]** accessed consecutively

- **Instructions:**
  - Temporal: loops cycle through the same instructions
  - Spatial: instructions referenced in sequence

- ***Being able to assess and tune the locality of code is a crucial skill for a performance programmer***

Locality Example

```
int sum_array_3d(double a[I][J][K])
{
  int i, j, k, sum = 0;

  for (k = 0; k < K; k++)
    for (j = 0; j < J; j++)
      for (i = 0; i < I; i++)
        sum += a[i][j][k];
  return sum;
}
```

Locality Example

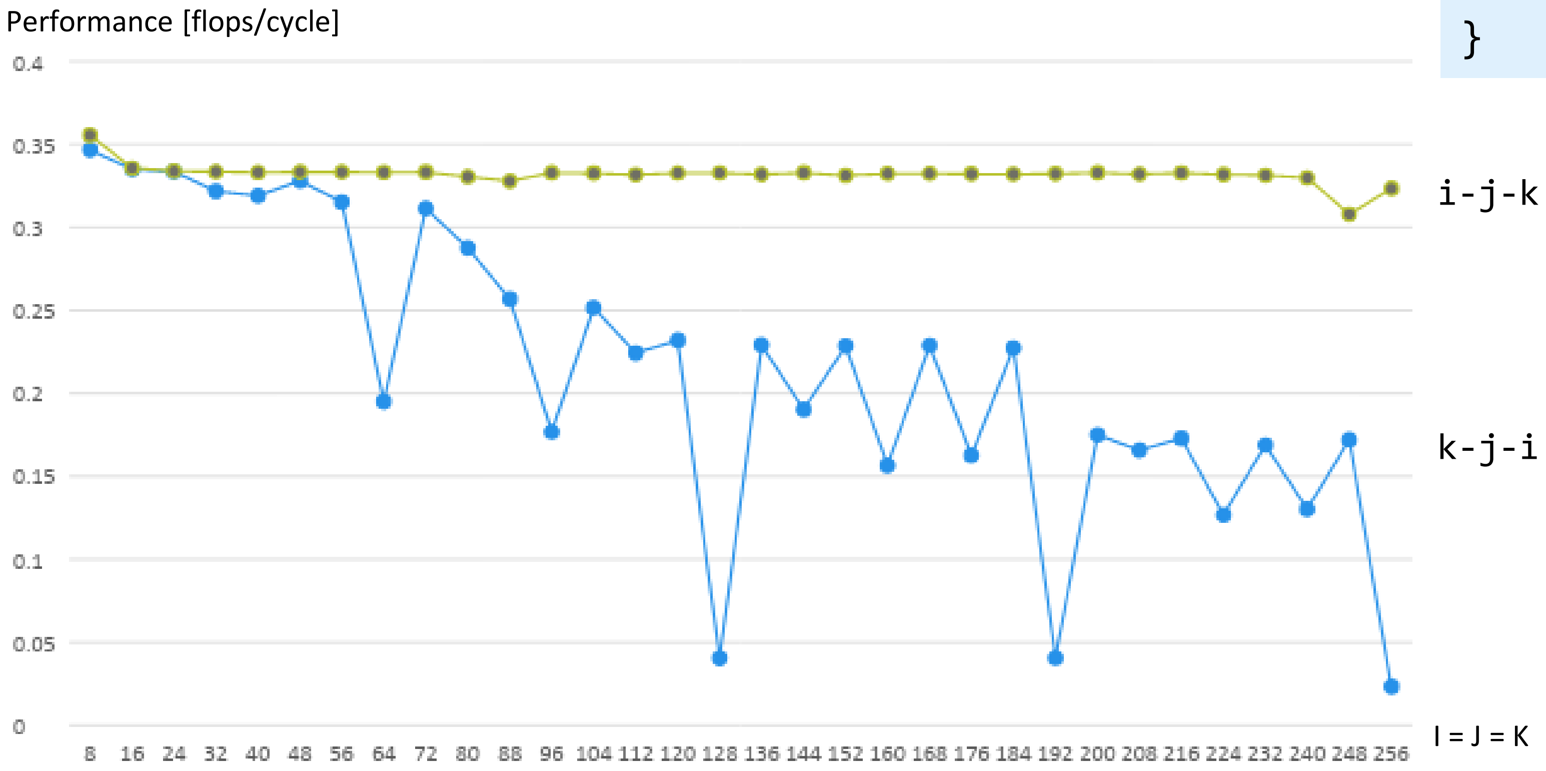
How to improve locality?

```
int sum_array_3d(double a[I][J][K])
{
  int i, j, k, sum = 0;

  for (k = 0; k < K; k++)
    for (j = 0; j < J; j++)
      for (i = 0; i < I; i++)
        sum += a[i][j][k];
  return sum;
}
```

Locality Example

How to improve locality?

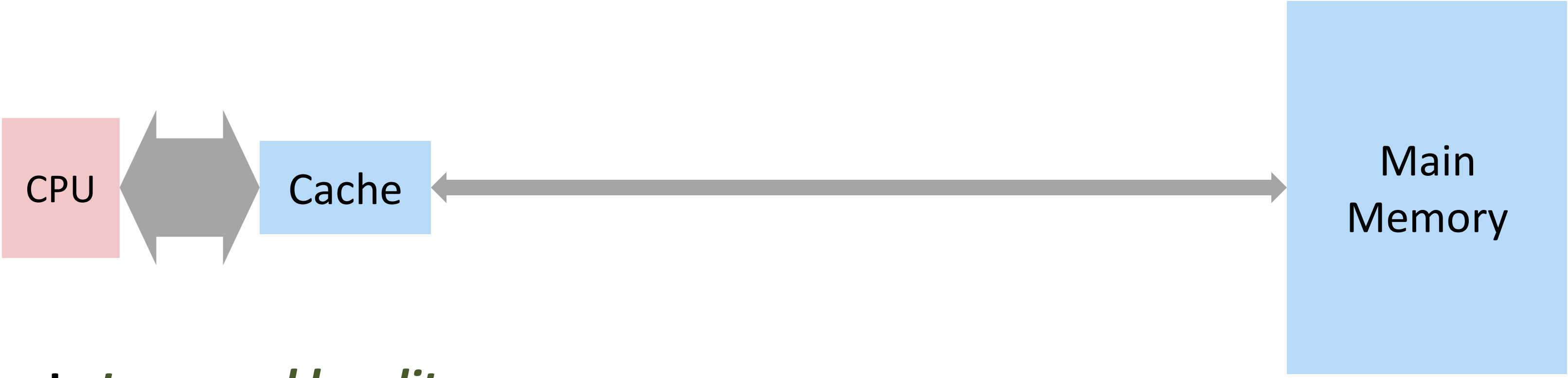
```
int sum_array_3d(double a[I][J][K])
{
  int i, j, k, sum = 0;

  for (k = 0; k < K; k++)
    for (j = 0; j < J; j++)
      for (i = 0; i < I; i++)
        sum += a[i][j][k];
  return sum;
}
```



CPU: Intel(R) Core(TM) i7-4980HQ CPU @ 2.80GHz
gcc: Apple LLVM version 8.0.0 (clang-800.0.42.1)
flags: -O3 -fno-vectorize

Cache

- *Definition:* **Computer memory with short access time used for the storage of frequently or recently used instructions or data**

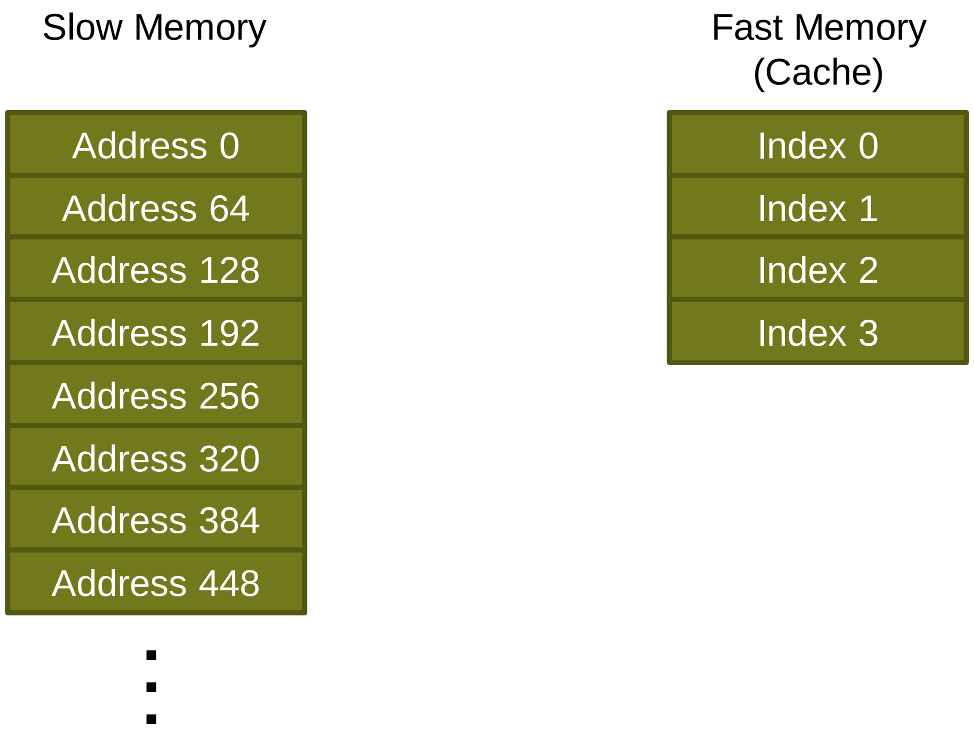


- **Naturally supports *temporal locality***

- ***Spatial locality* is supported by transferring data in blocks**
  - E.g., Intel’s Core family: one block = 64 B = 8 doubles

Cache Structure

Simplest design: direct mapped!



Slow Memory

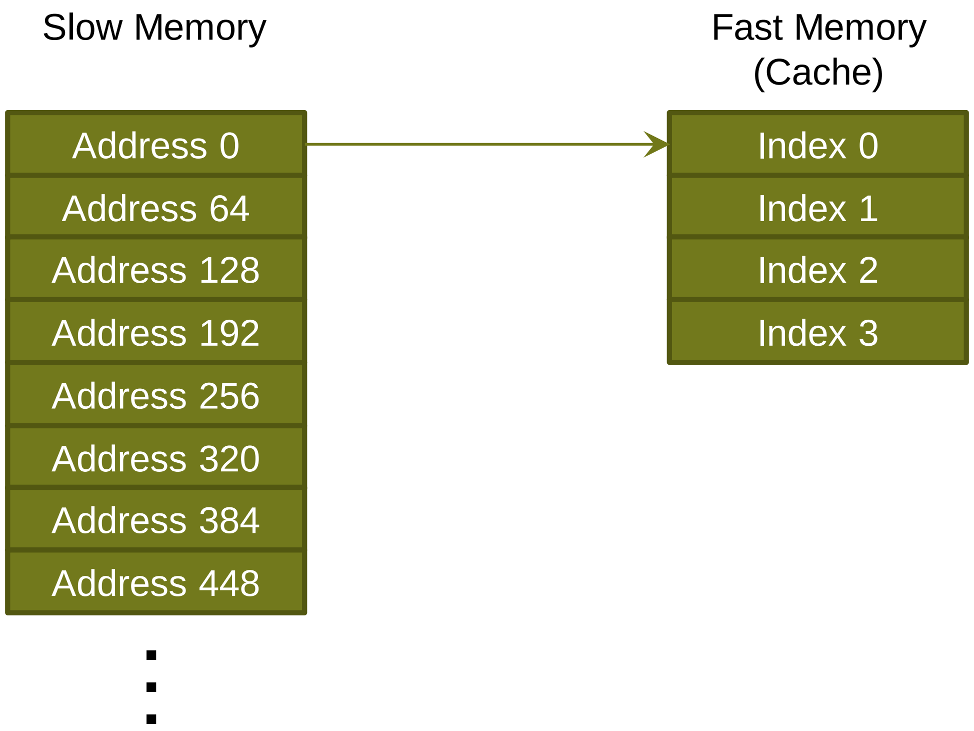
Address 0
Address 64
Address 128
Address 192
Address 256
Address 320
Address 384
Address 448
⋮

Fast Memory (Cache)

Index 0
Index 1
Index 2
Index 3

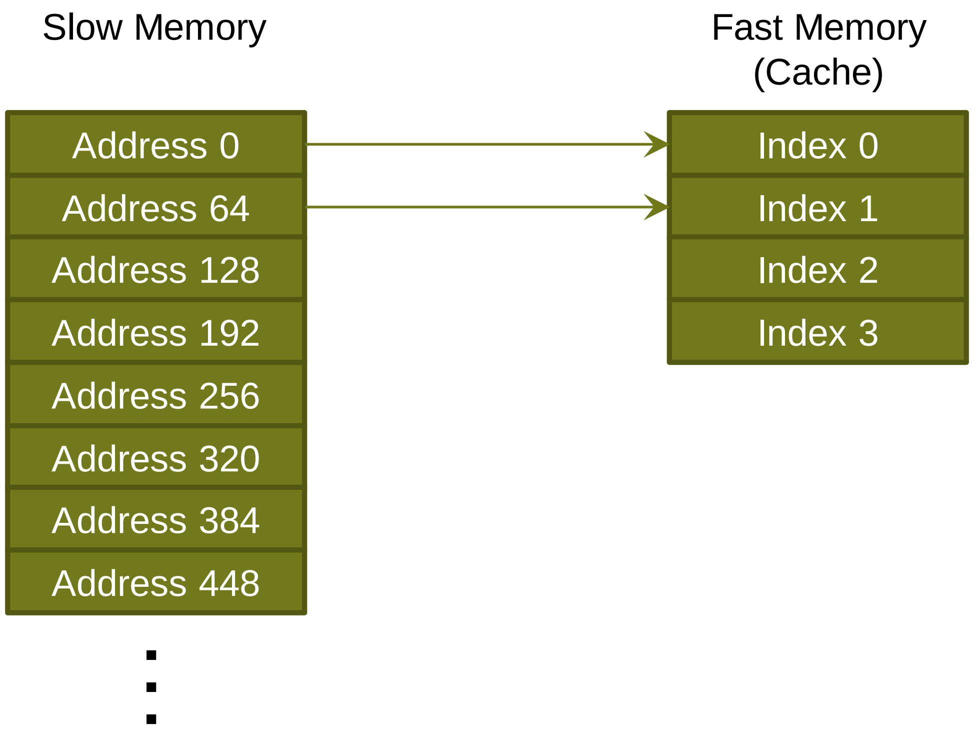
Cache Structure

Simplest design: direct mapped!



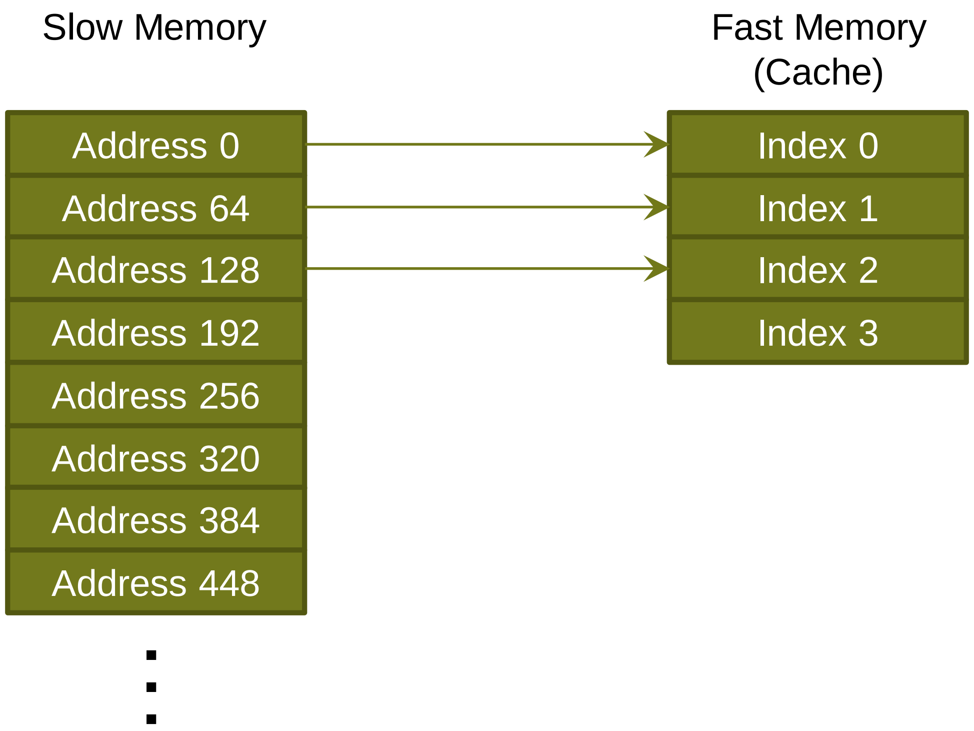
Cache Structure

Simplest design: direct mapped!



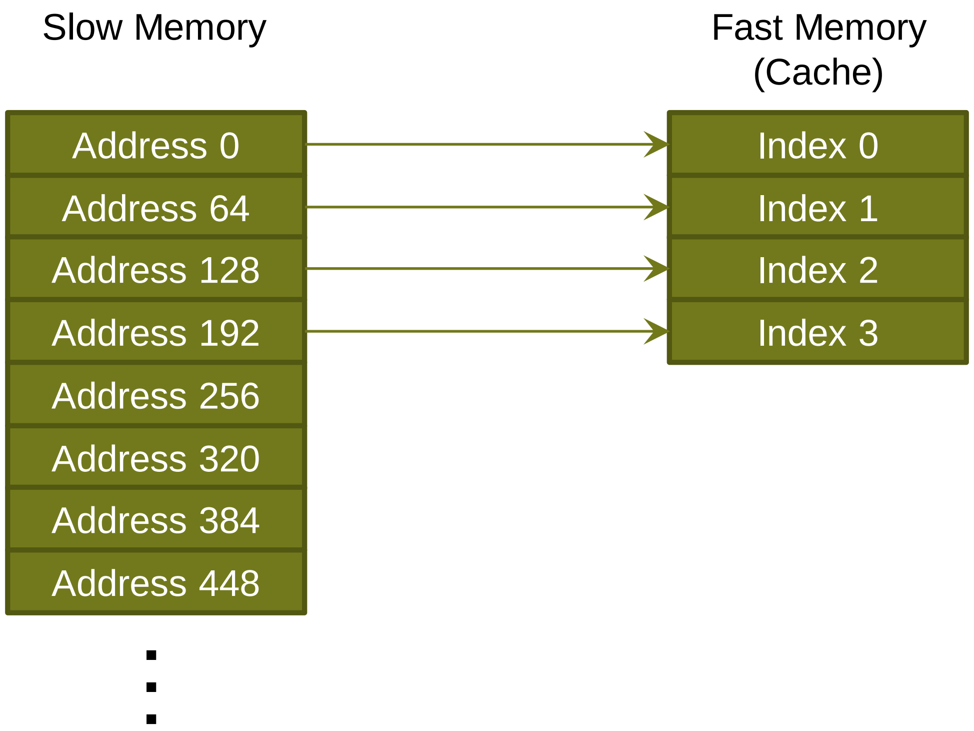
Cache Structure

Simplest design: direct mapped!



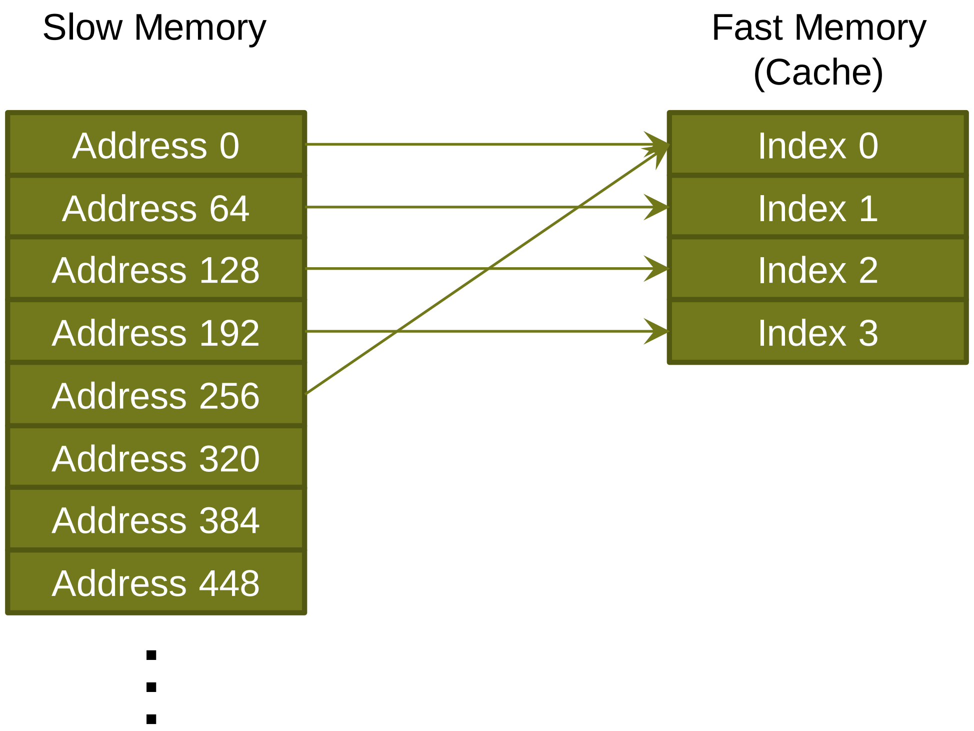
Cache Structure

Simplest design: direct mapped!



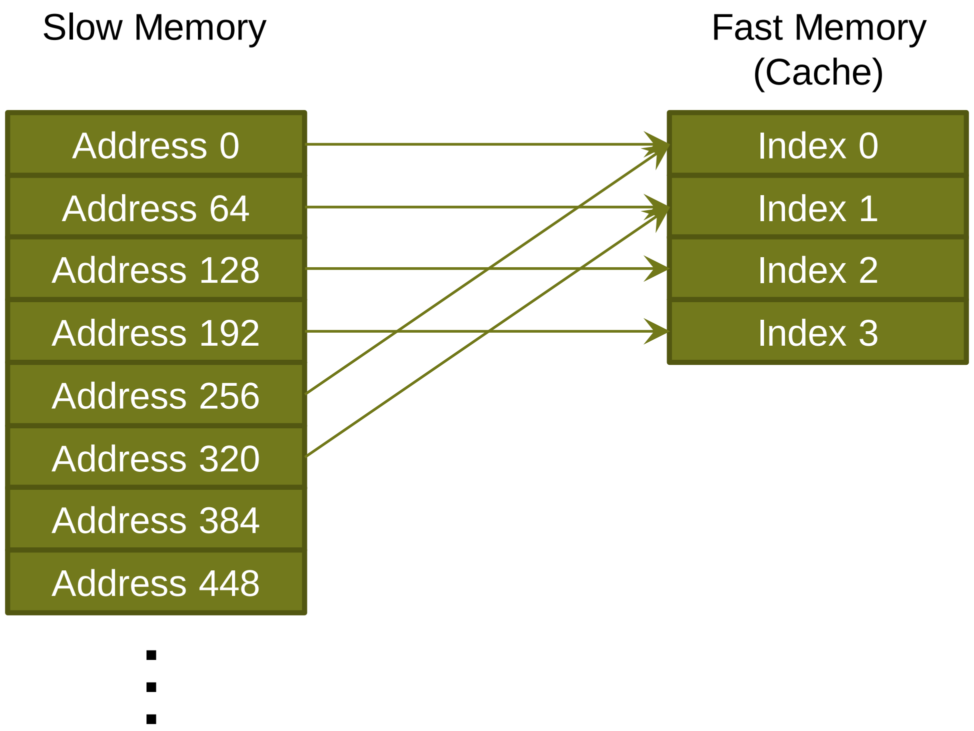
Cache Structure

Simplest design: direct mapped!



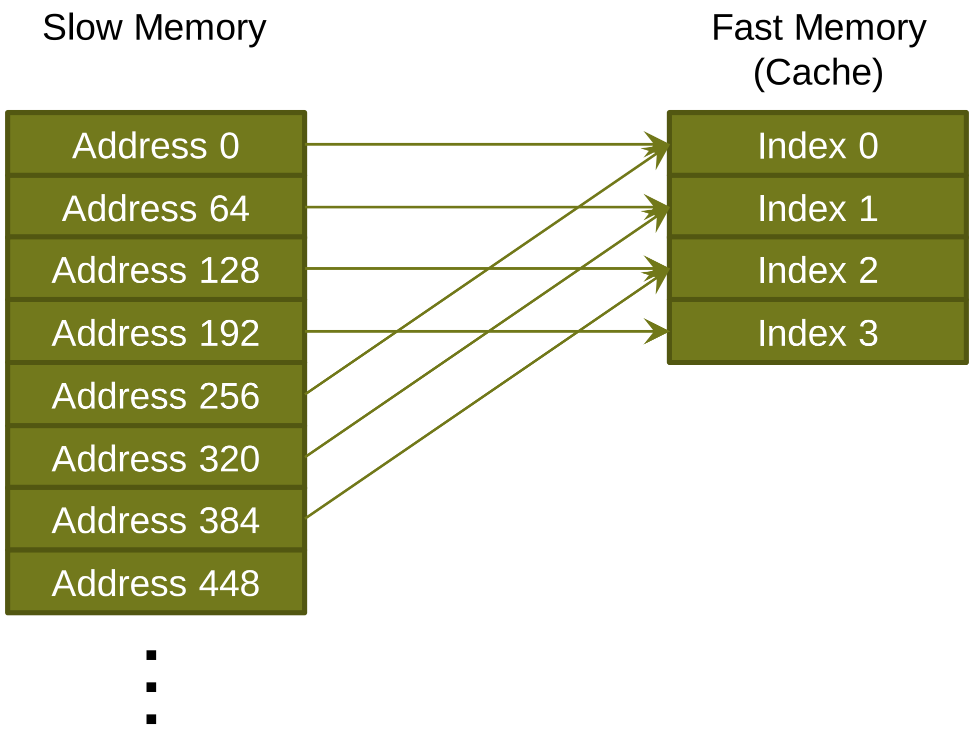
Cache Structure

Simplest design: direct mapped!



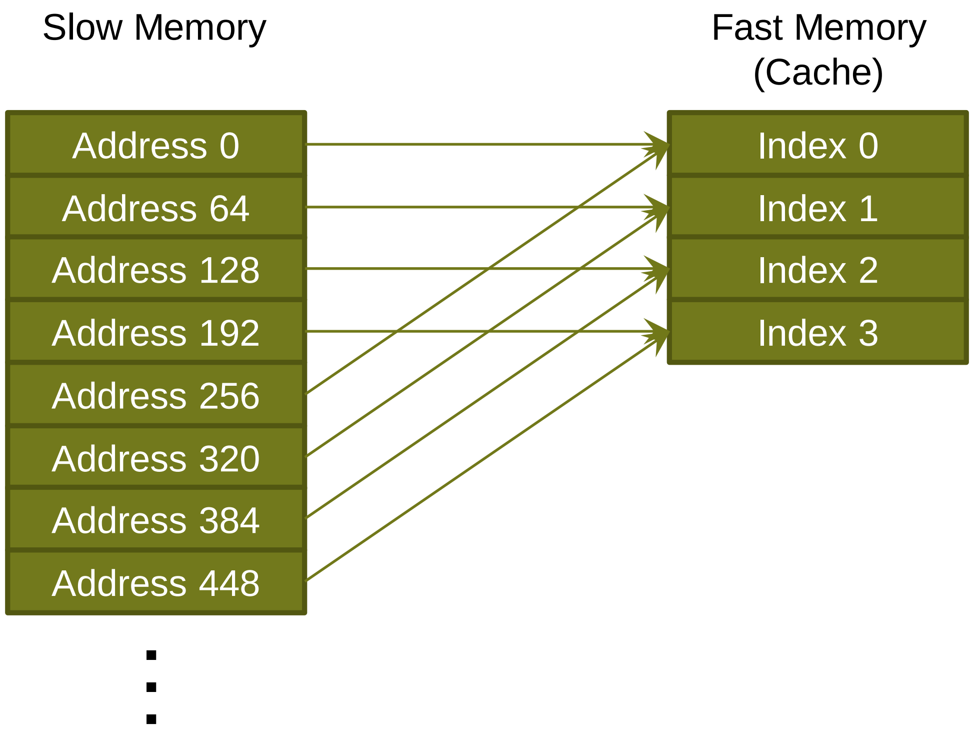
Cache Structure

Simplest design: direct mapped!



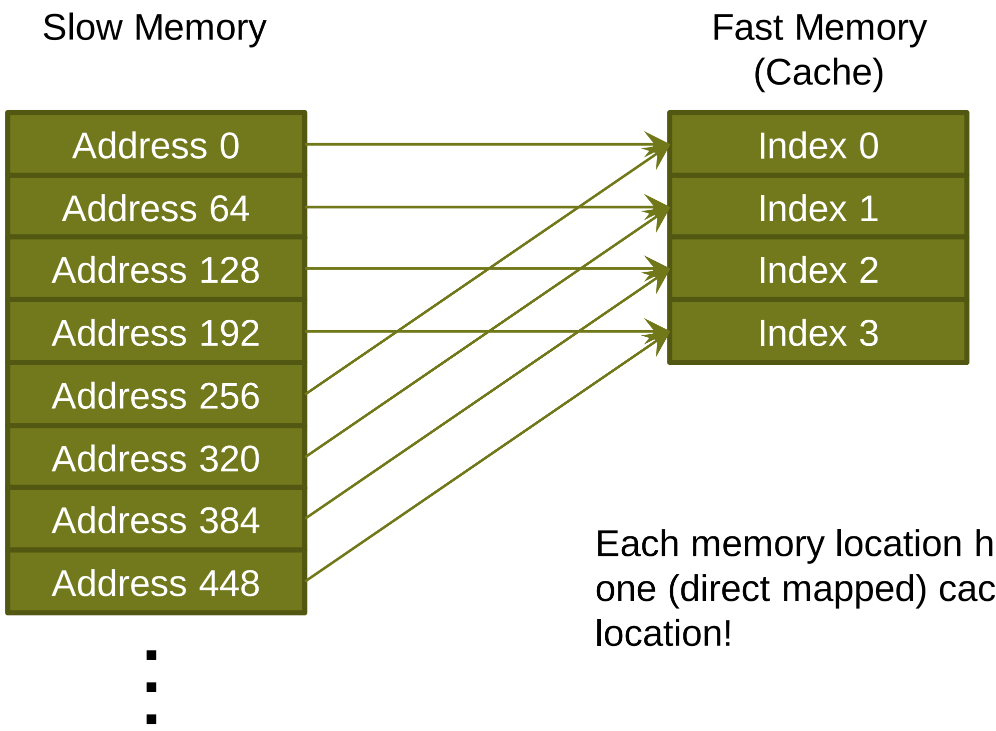
Cache Structure

Simplest design: direct mapped!



Cache Structure

Simplest design: direct mapped!

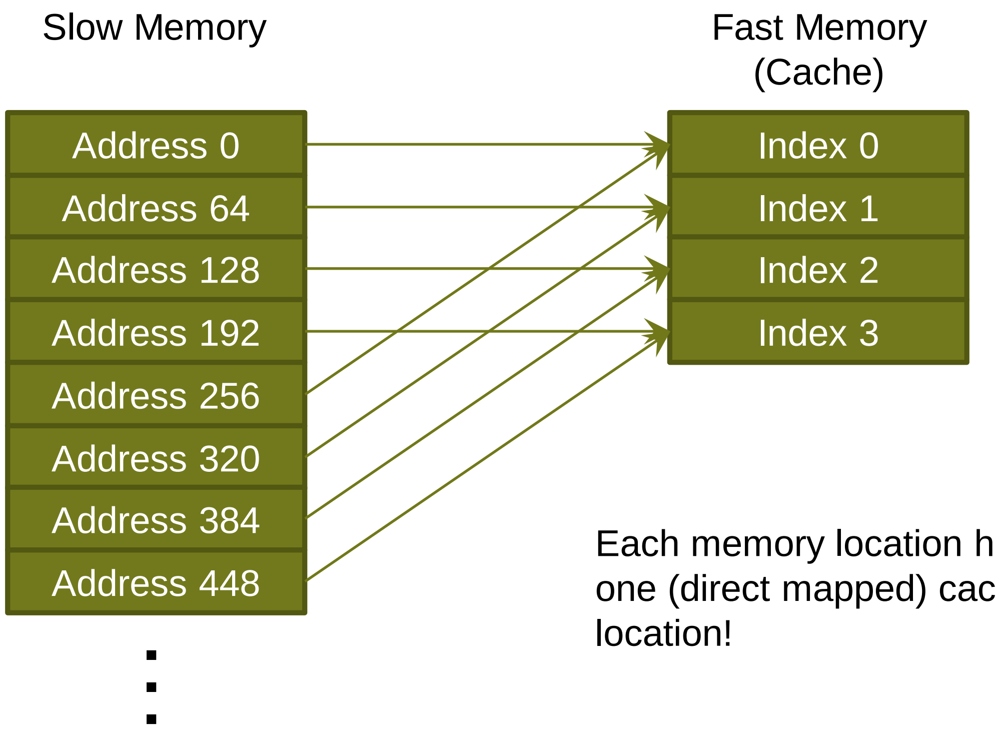


Each memory location has one (direct mapped) cache location!

Cache Structure

Simplest design: direct mapped!

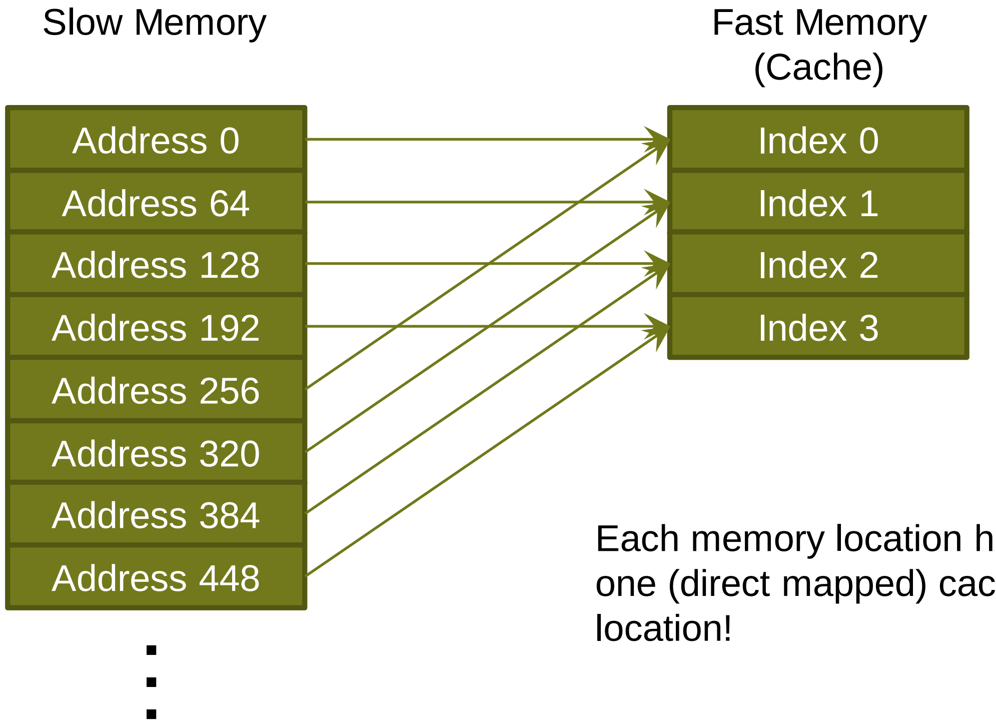
Adding 2-way associativity



Each memory location has one (direct mapped) cache location!

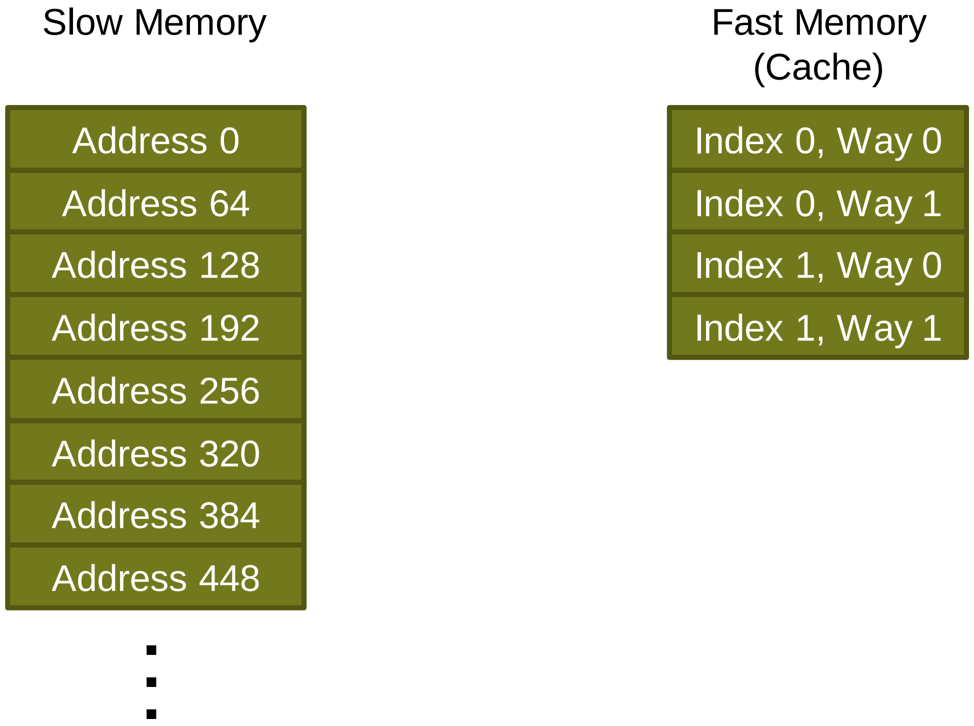
Cache Structure

Simplest design: direct mapped!



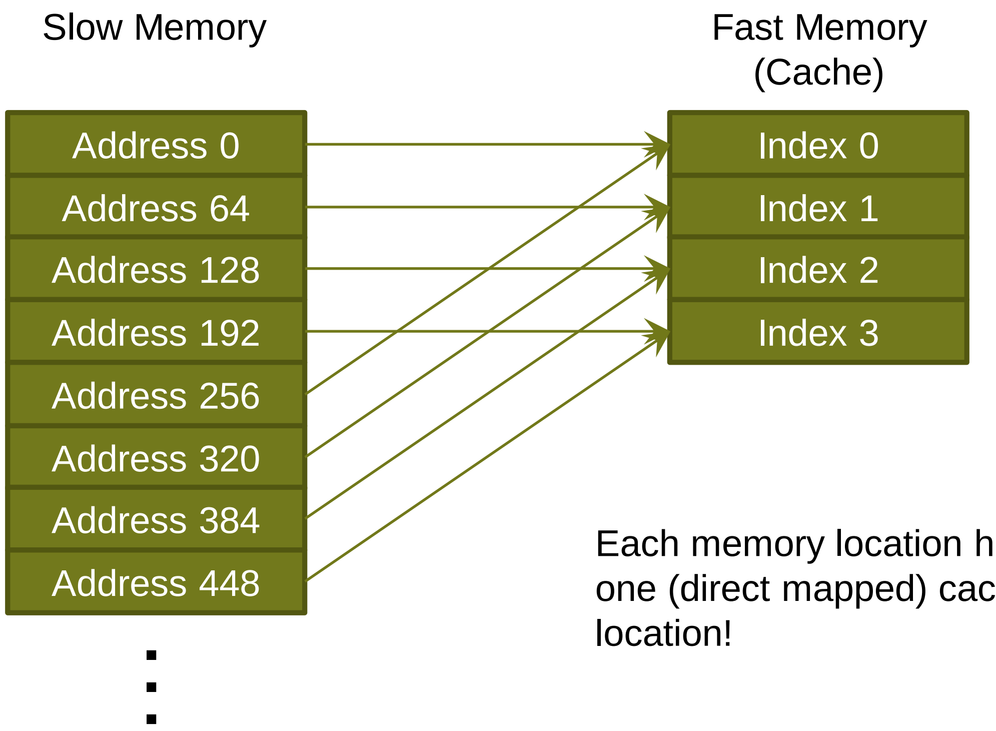
Each memory location has one (direct mapped) cache location!

Adding 2-way associativity



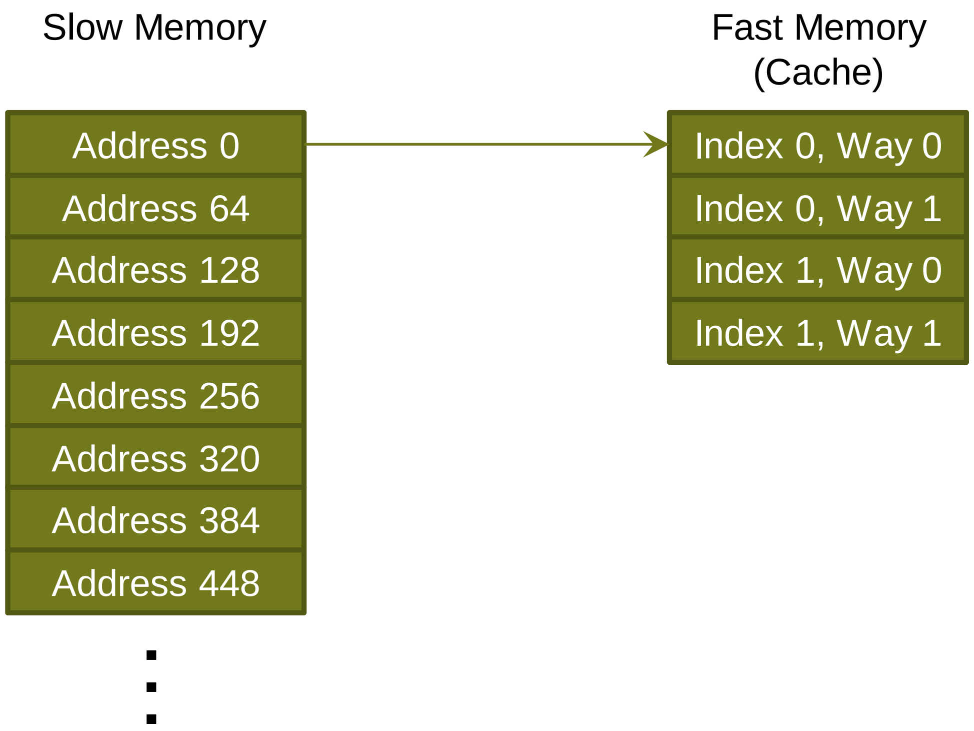
Cache Structure

Simplest design: direct mapped!



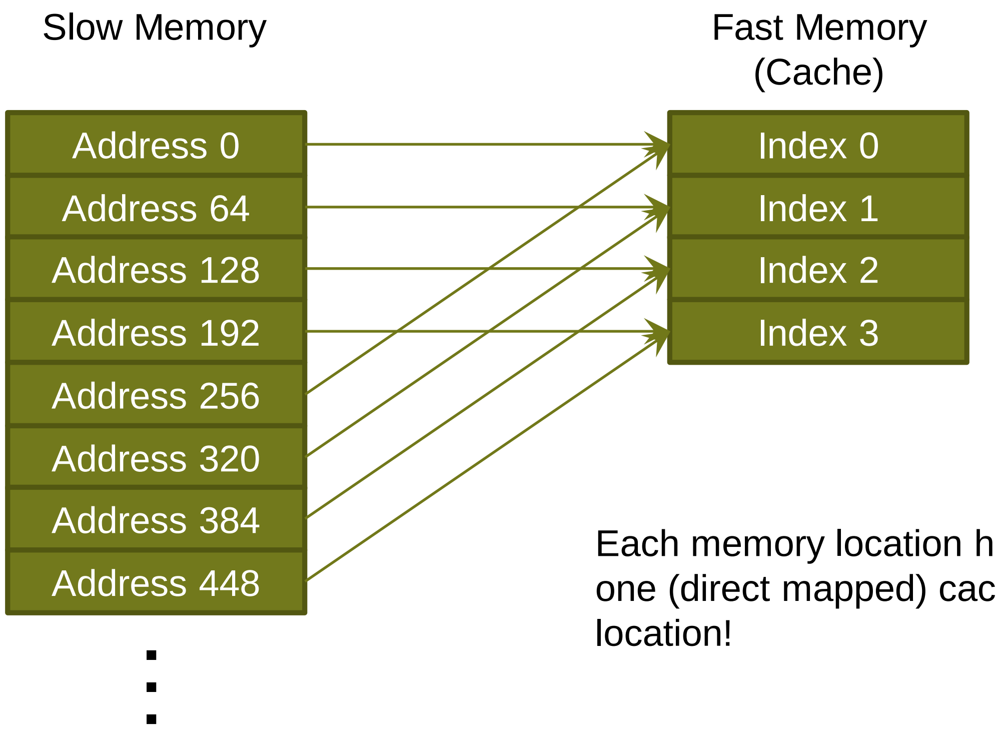
Each memory location has one (direct mapped) cache location!

Adding 2-way associativity



Cache Structure

Simplest design: direct mapped!



Slow Memory

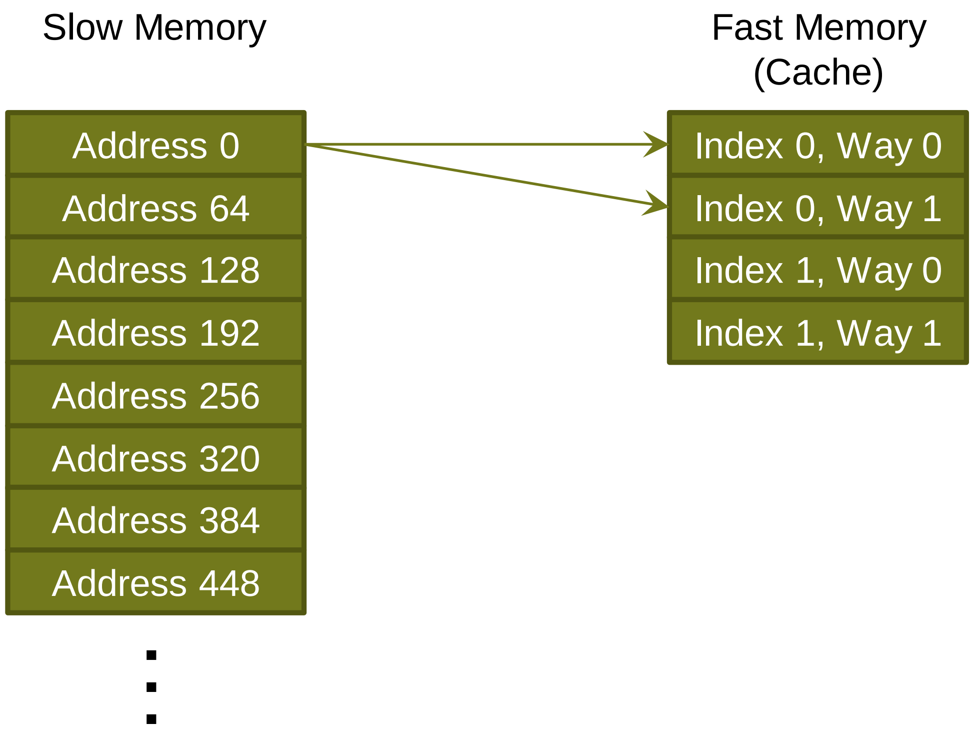
Address 0
Address 64
Address 128
Address 192
Address 256
Address 320
Address 384
Address 448
⋮

Fast Memory
(Cache)

Index 0
Index 1
Index 2
Index 3

Each memory location has one (direct mapped) cache location!

Adding 2-way associativity



Slow Memory

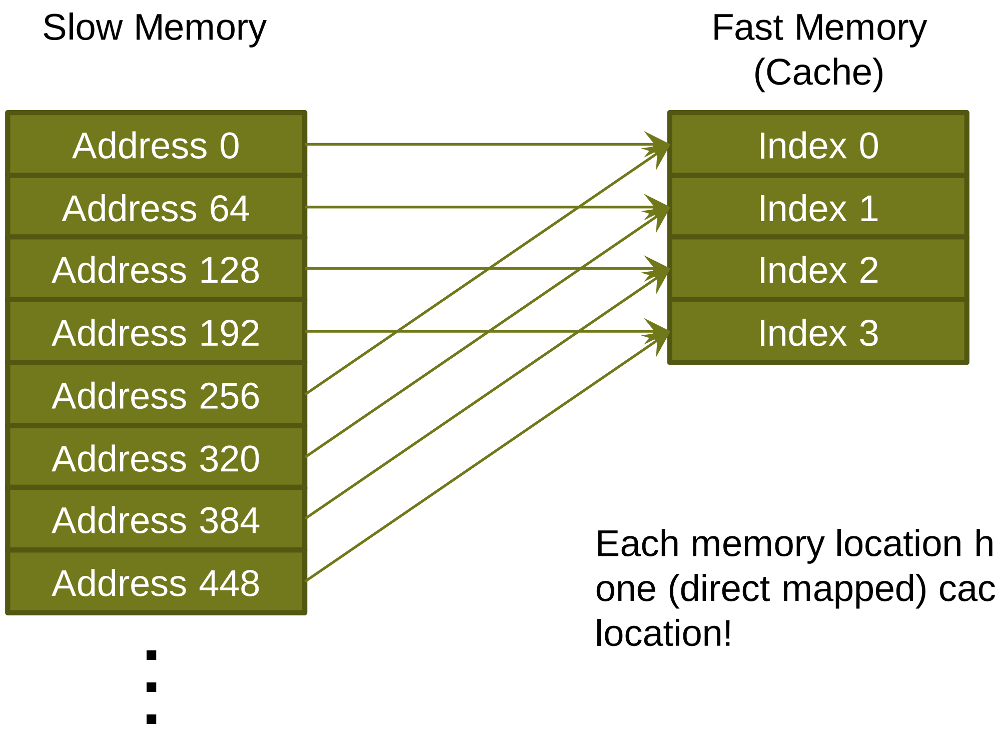
Address 0
Address 64
Address 128
Address 192
Address 256
Address 320
Address 384
Address 448
⋮

Fast Memory
(Cache)

Index 0, Way 0
Index 0, Way 1
Index 1, Way 0
Index 1, Way 1

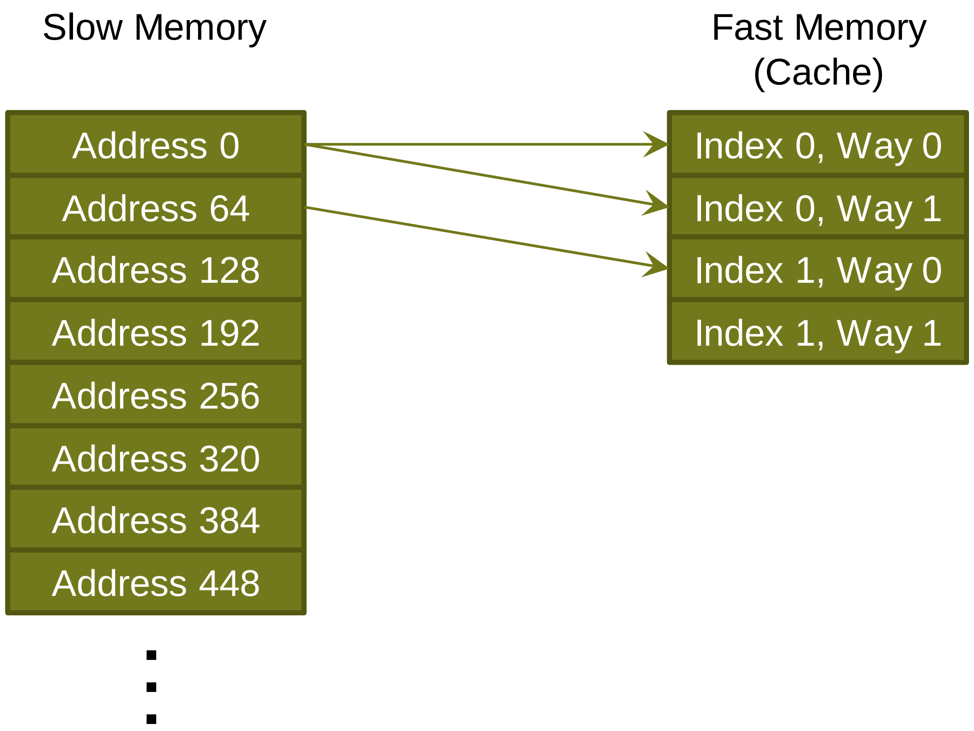
Cache Structure

Simplest design: direct mapped!



Each memory location has one (direct mapped) cache location!

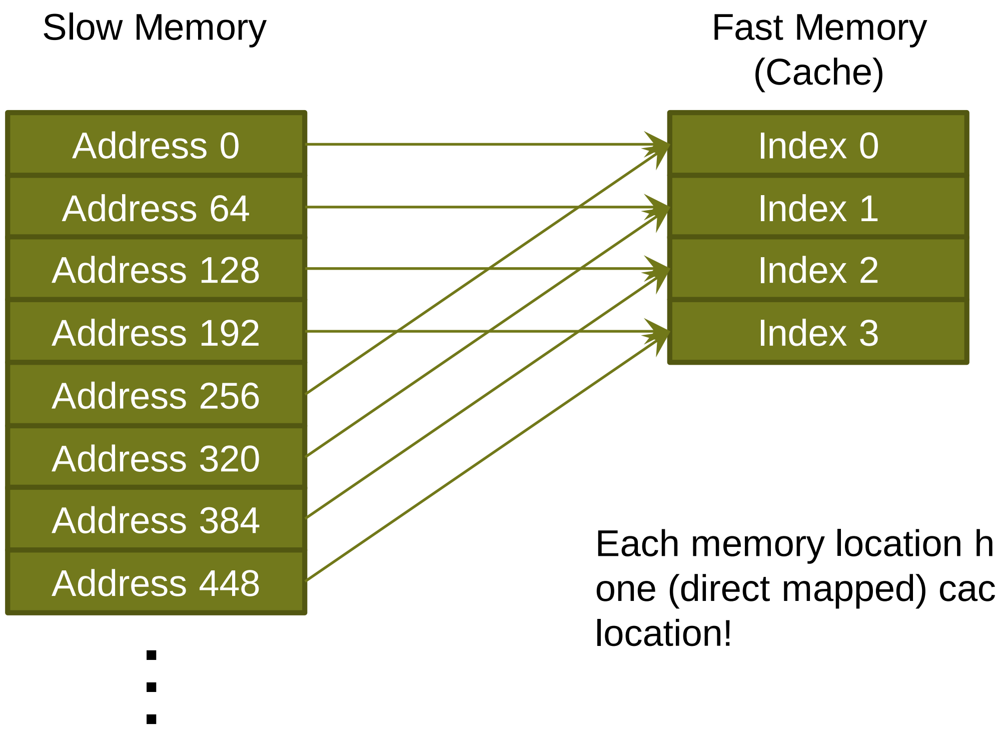
Adding 2-way associativity



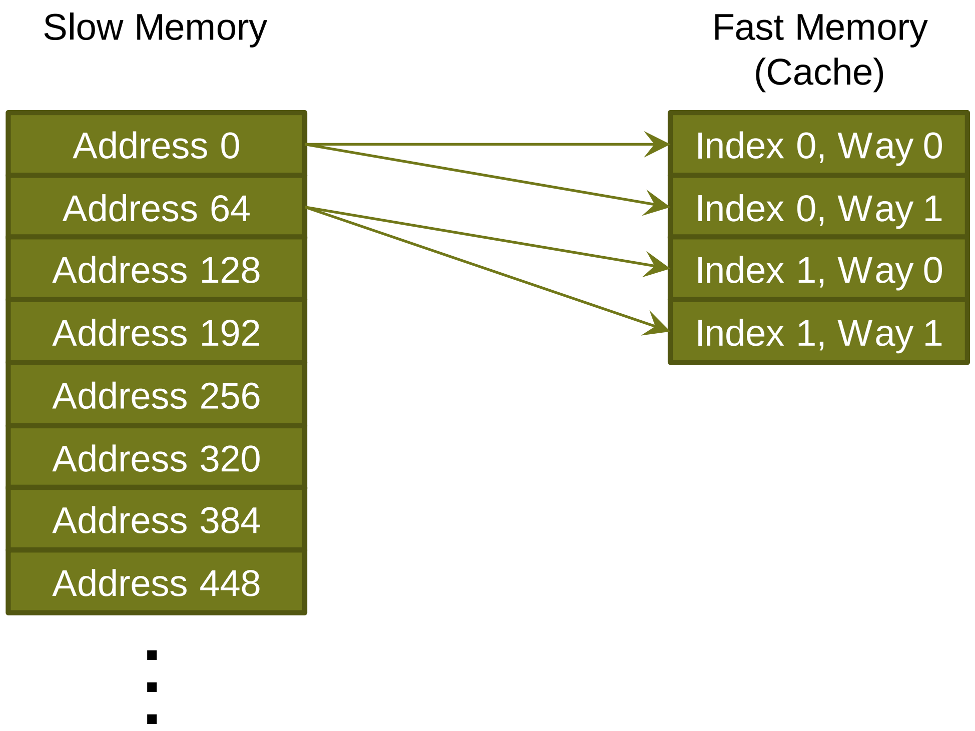
Cache Structure

Simplest design: direct mapped!

Adding 2-way associativity

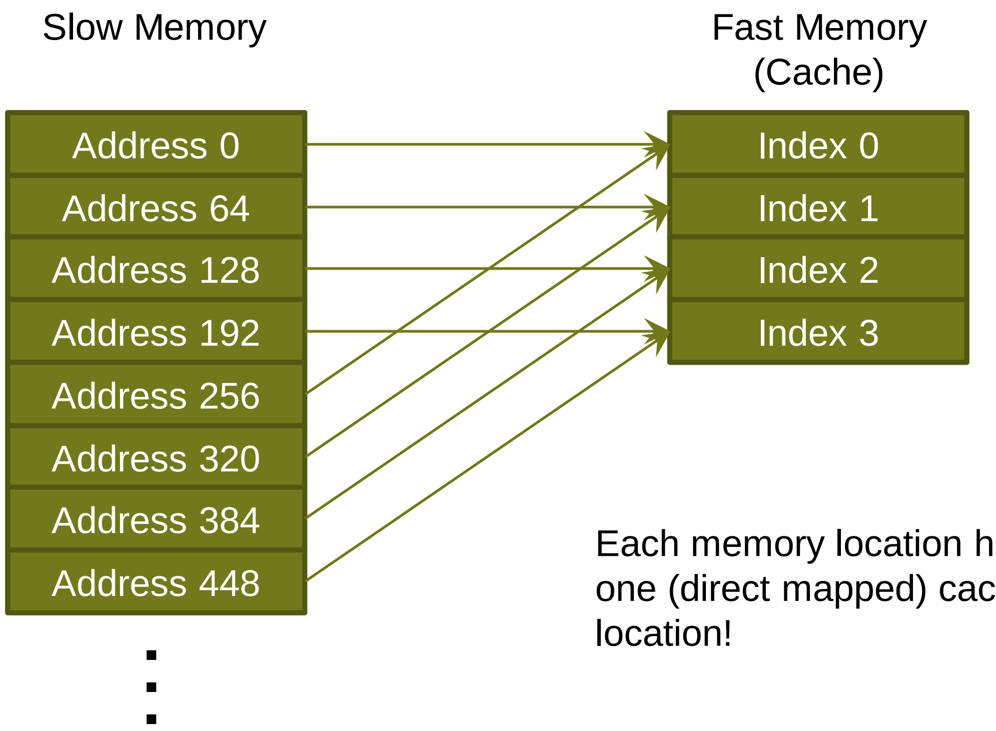


Each memory location has one (direct mapped) cache location!



Cache Structure

Simplest design: direct mapped!



Slow Memory

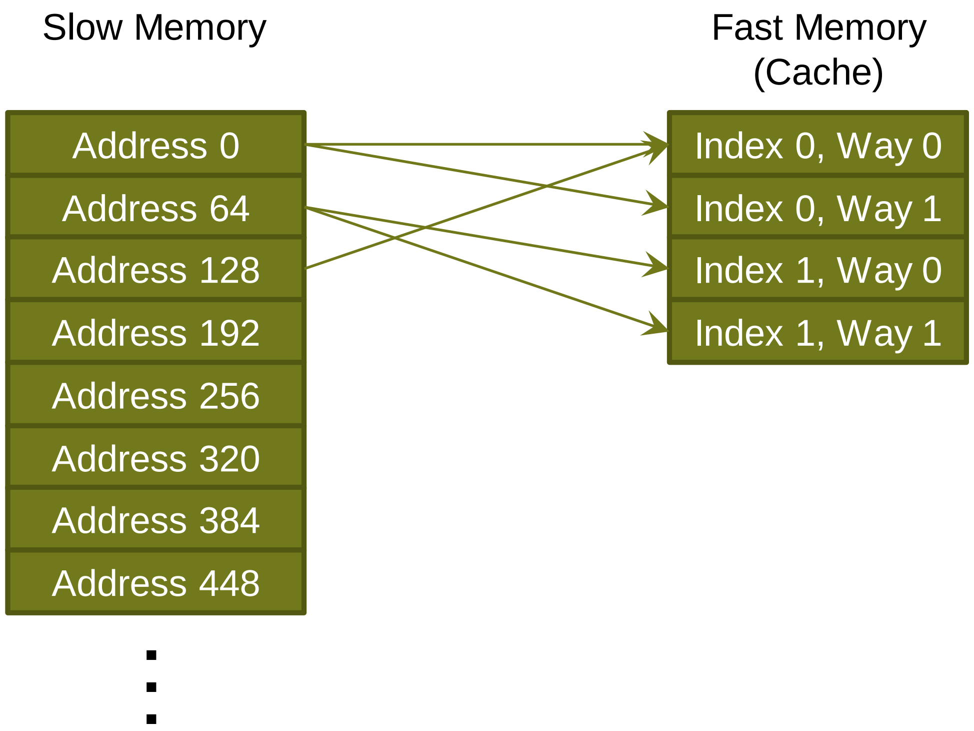
Fast Memory (Cache)

Address 0
Address 64
Address 128
Address 192
Address 256
Address 320
Address 384
Address 448

Index 0
Index 1
Index 2
Index 3

Each memory location has one (direct mapped) cache location!

Adding 2-way associativity



Slow Memory

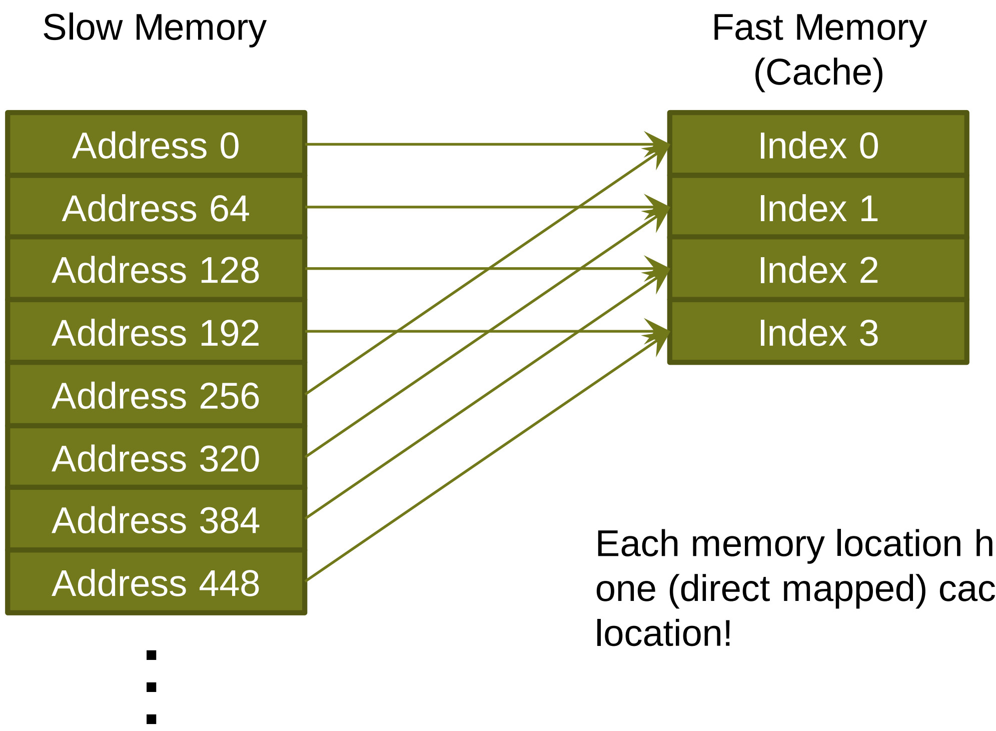
Fast Memory (Cache)

Address 0
Address 64
Address 128
Address 192
Address 256
Address 320
Address 384
Address 448

Index 0, Way 0
Index 0, Way 1
Index 1, Way 0
Index 1, Way 1

Cache Structure

Simplest design: direct mapped!



Slow Memory

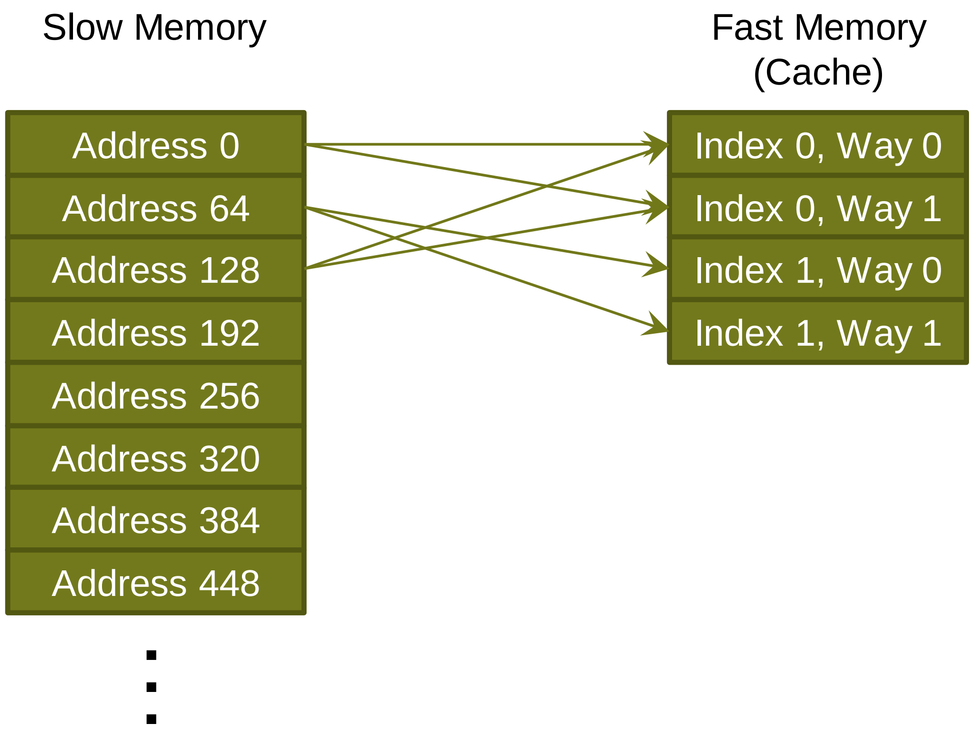
Address 0
Address 64
Address 128
Address 192
Address 256
Address 320
Address 384
Address 448
⋮

Fast Memory
(Cache)

Index 0
Index 1
Index 2
Index 3

Each memory location has one (direct mapped) cache location!

Adding 2-way associativity



Slow Memory

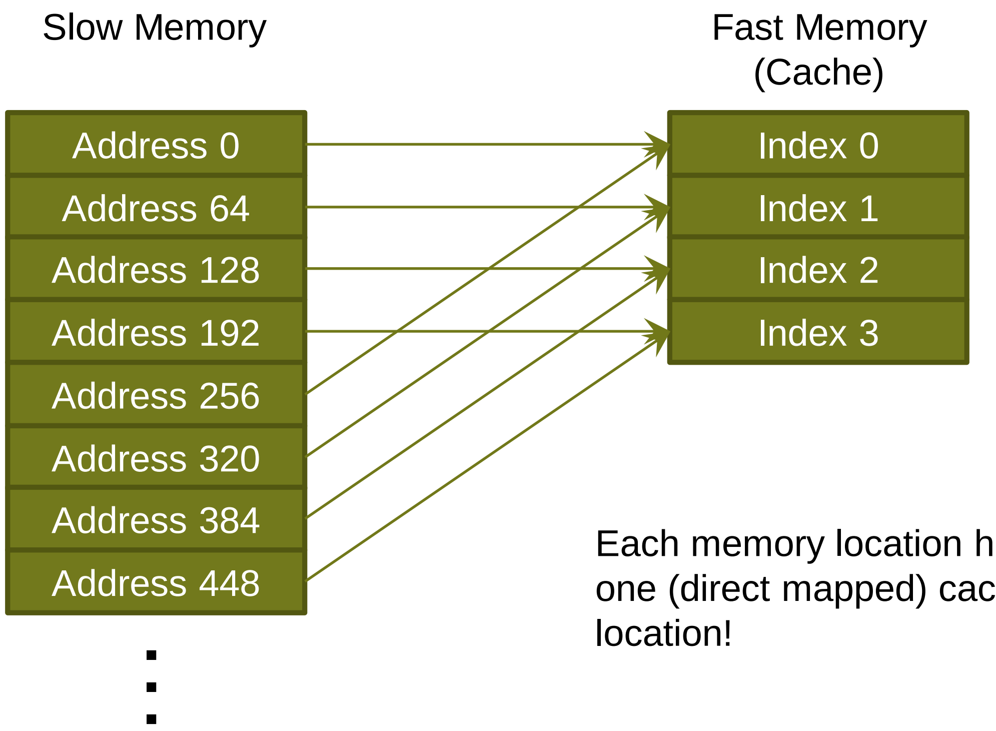
Address 0
Address 64
Address 128
Address 192
Address 256
Address 320
Address 384
Address 448
⋮

Fast Memory
(Cache)

Index 0, Way 0
Index 0, Way 1
Index 1, Way 0
Index 1, Way 1

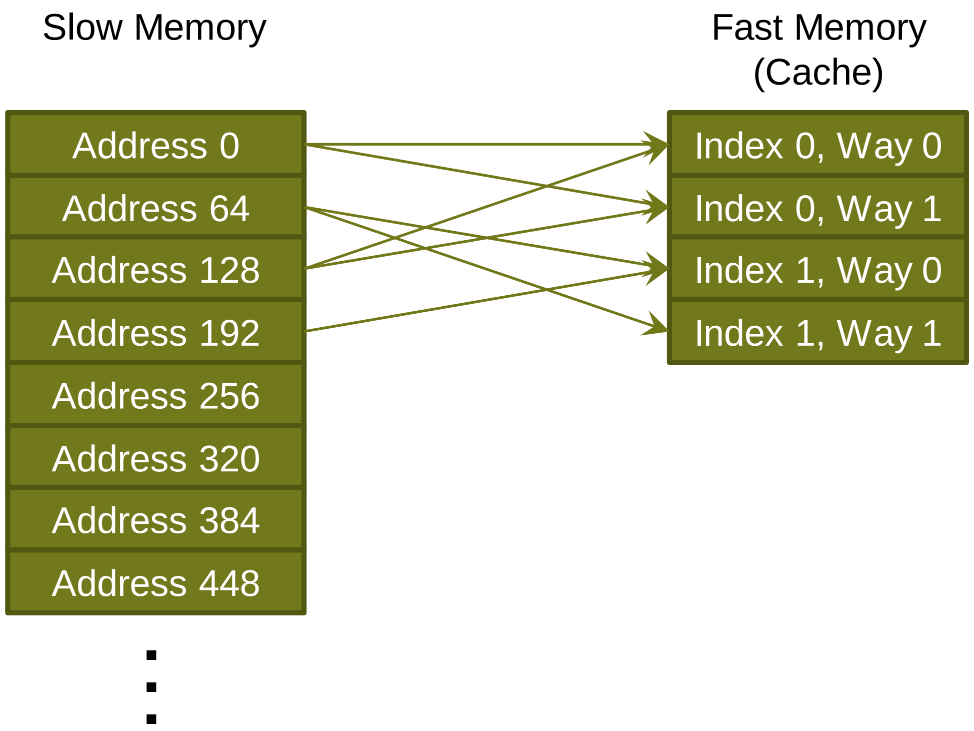
Cache Structure

Simplest design: direct mapped!



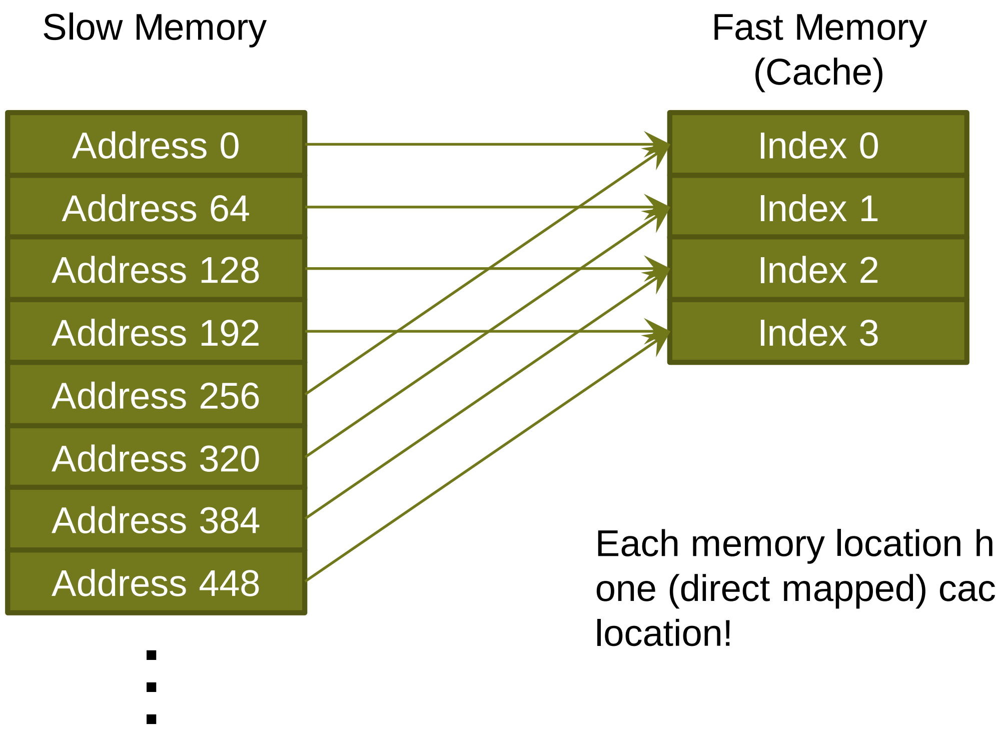
Each memory location has one (direct mapped) cache location!

Adding 2-way associativity



Cache Structure

Simplest design: direct mapped!



Slow Memory

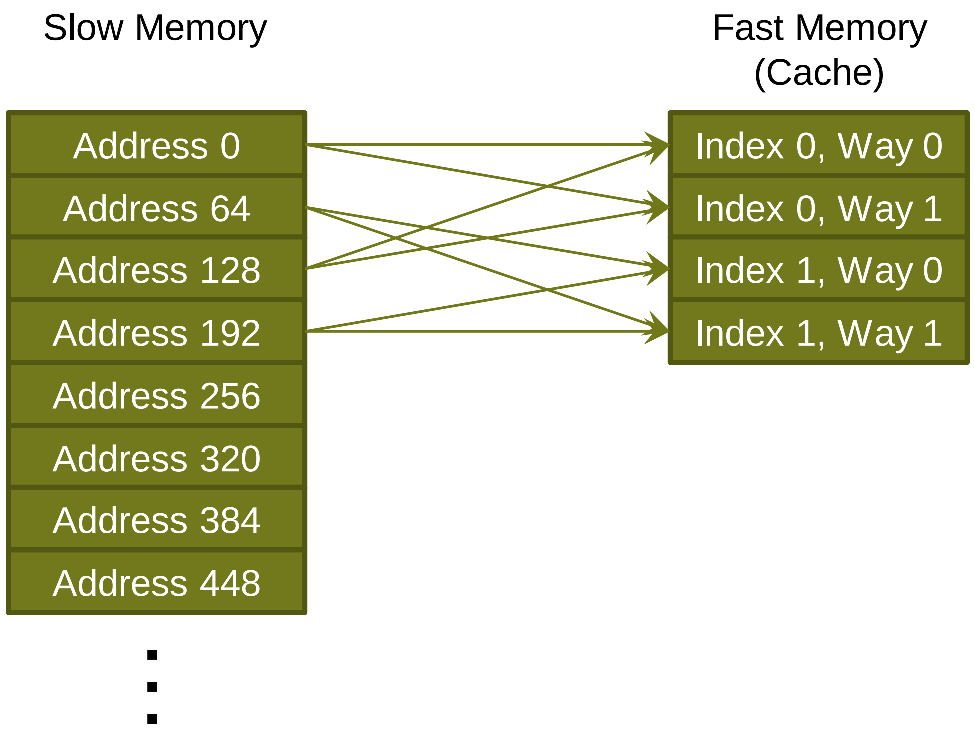
Address 0
Address 64
Address 128
Address 192
Address 256
Address 320
Address 384
Address 448
⋮

Fast Memory
(Cache)

Index 0
Index 1
Index 2
Index 3

Each memory location has one (direct mapped) cache location!

Adding 2-way associativity



Slow Memory

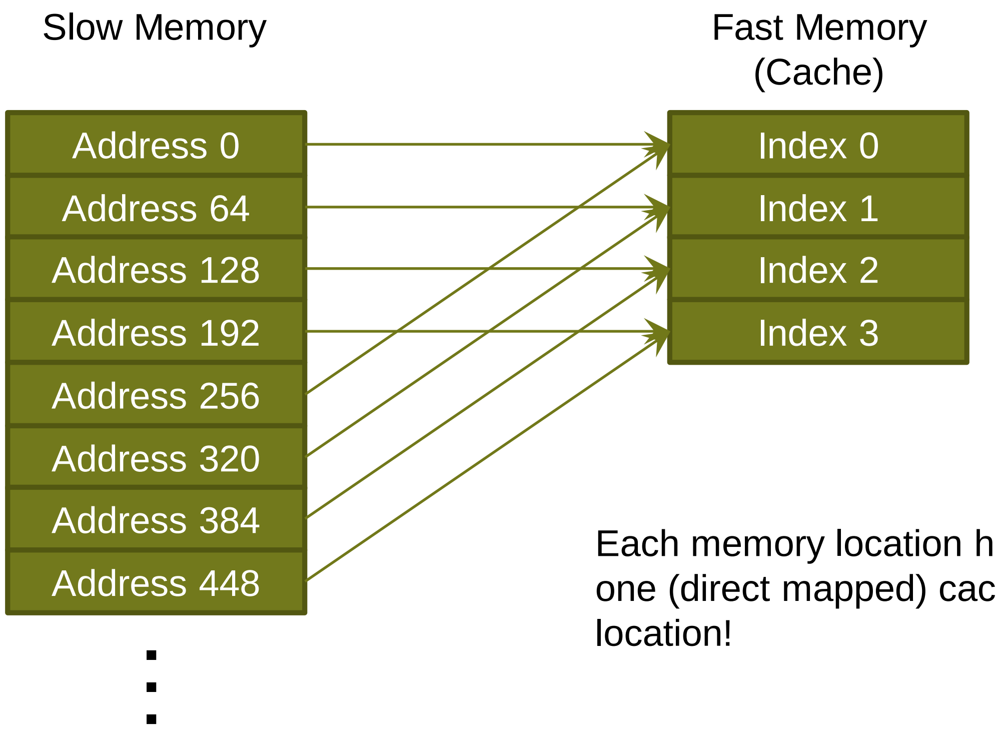
Address 0
Address 64
Address 128
Address 192
Address 256
Address 320
Address 384
Address 448
⋮

Fast Memory
(Cache)

Index 0, Way 0
Index 0, Way 1
Index 1, Way 0
Index 1, Way 1

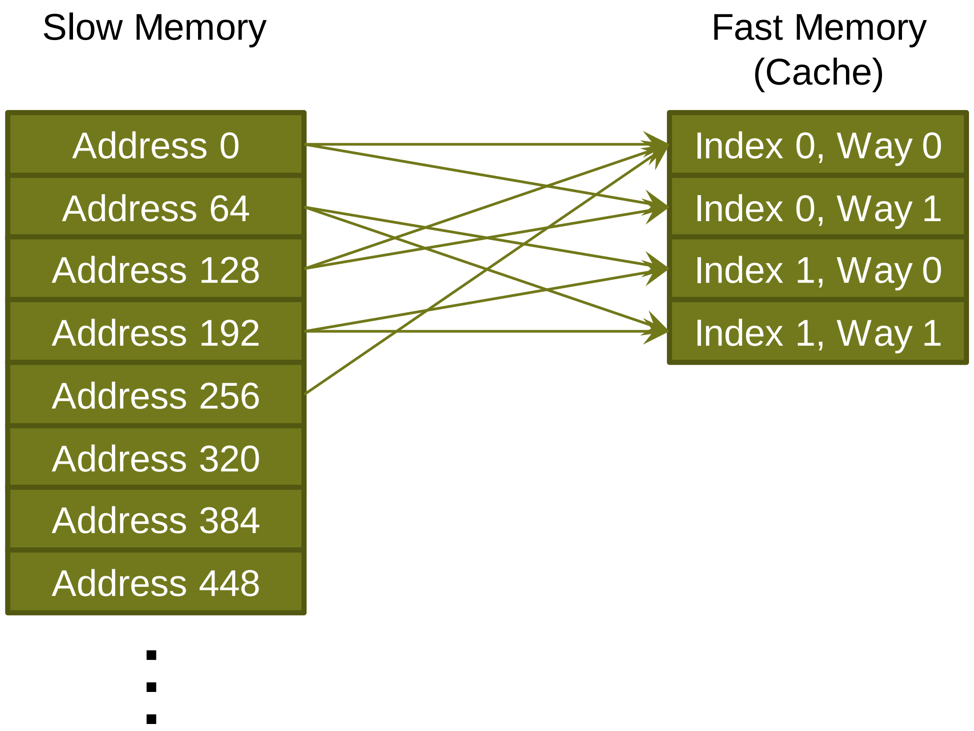
Cache Structure

Simplest design: direct mapped!



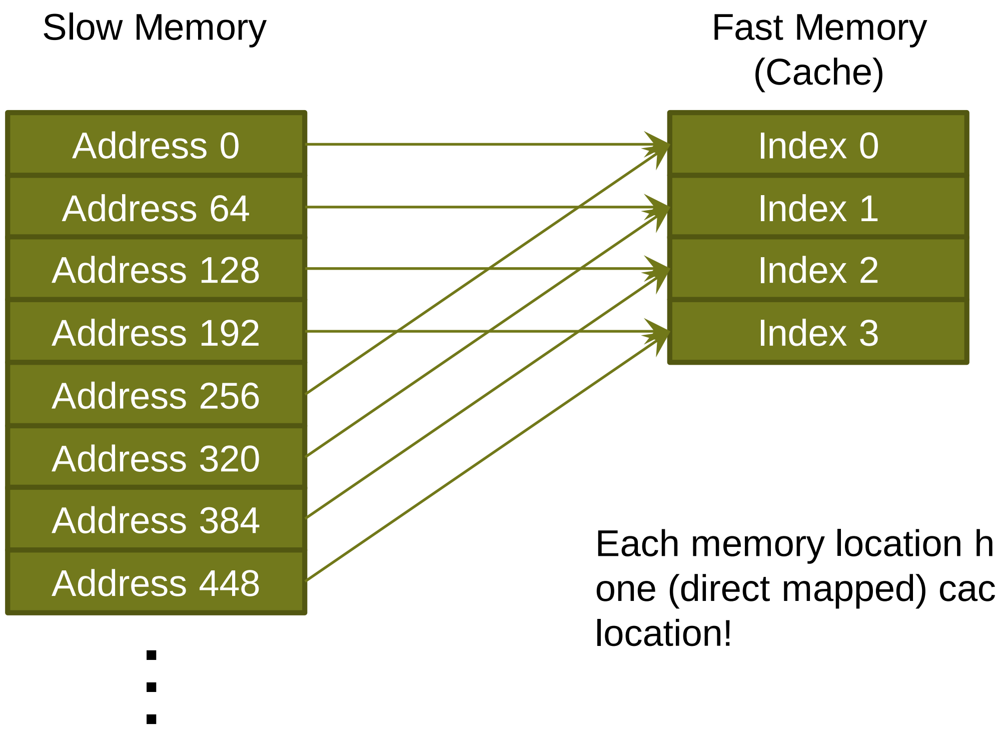
Each memory location has one (direct mapped) cache location!

Adding 2-way associativity



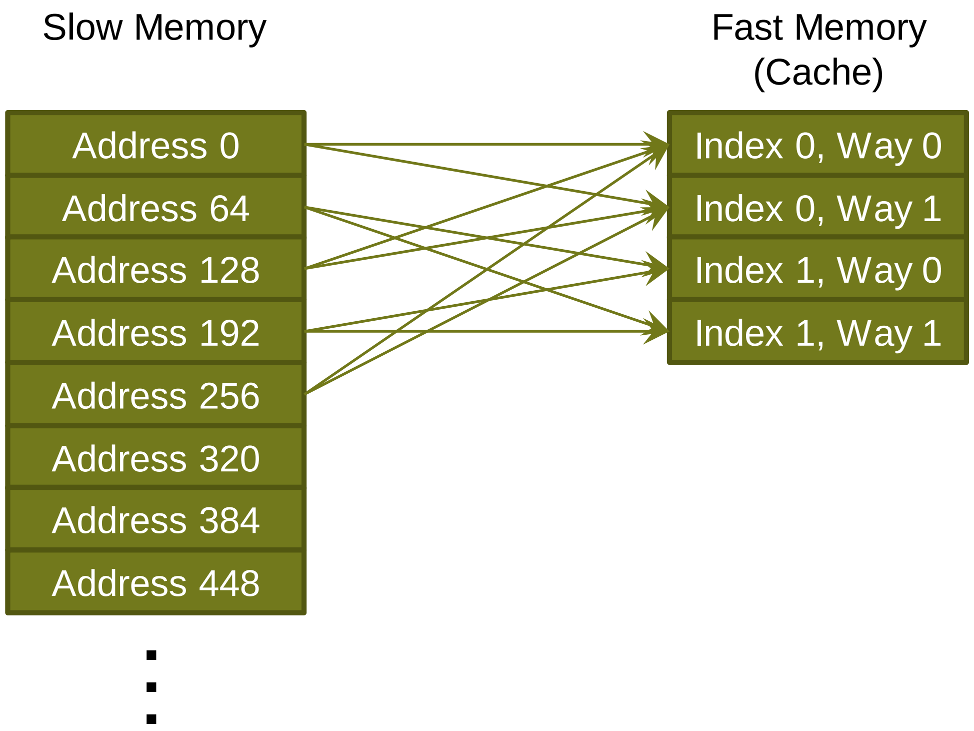
Cache Structure

Simplest design: direct mapped!



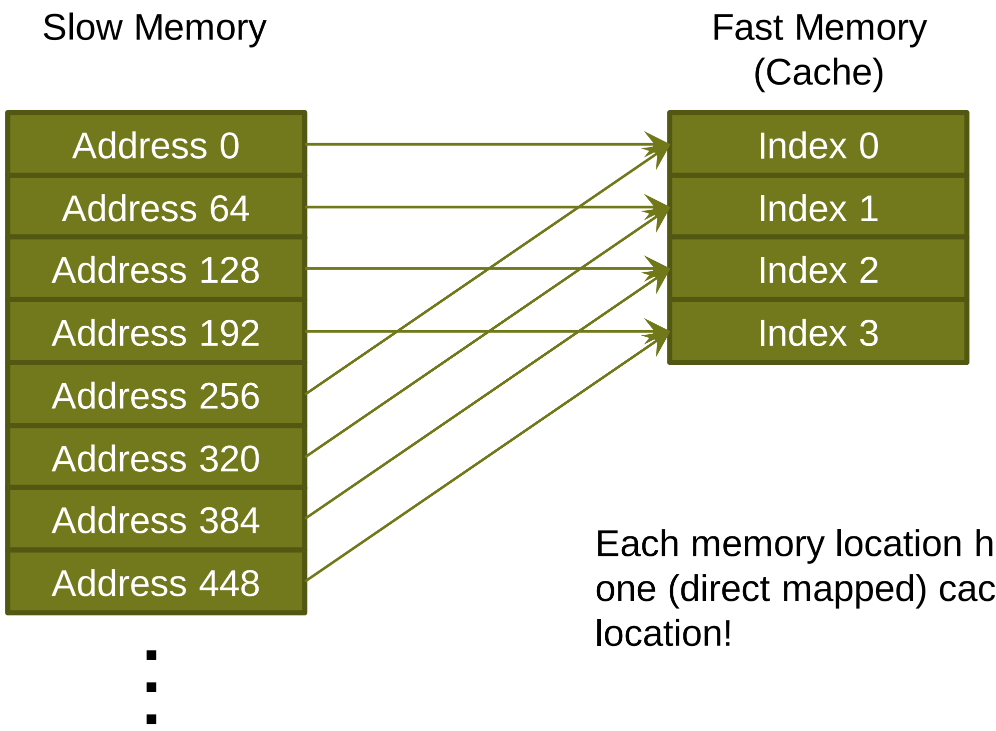
Each memory location has one (direct mapped) cache location!

Adding 2-way associativity



Cache Structure

Simplest design: direct mapped!



Slow Memory

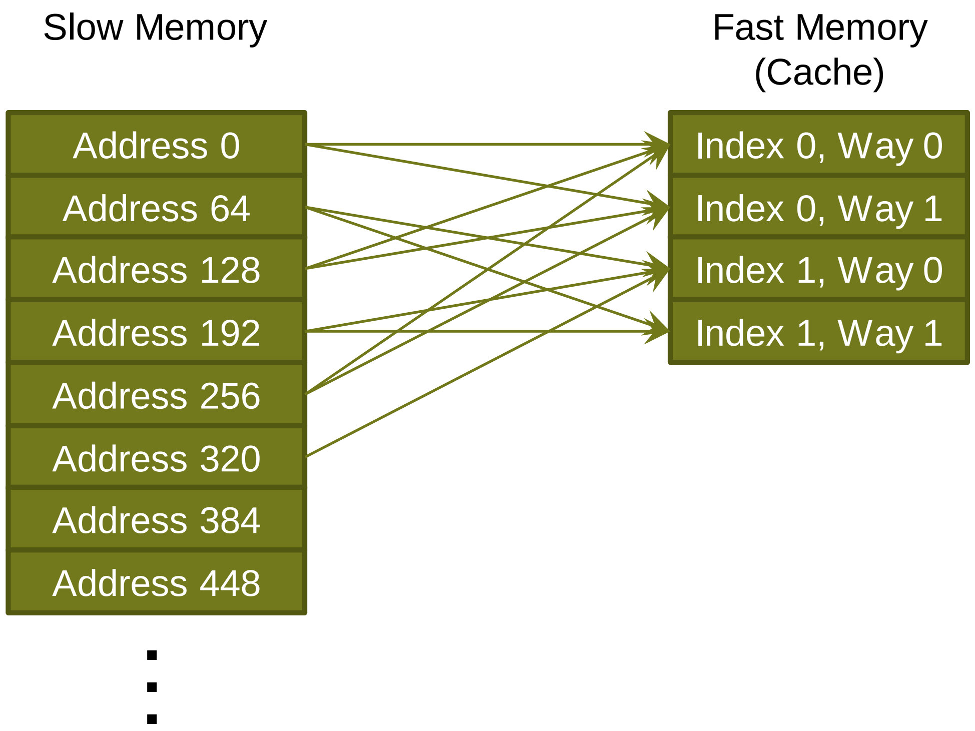
Address 0
Address 64
Address 128
Address 192
Address 256
Address 320
Address 384
Address 448
⋮

Fast Memory
(Cache)

Index 0
Index 1
Index 2
Index 3

Each memory location has one (direct mapped) cache location!

Adding 2-way associativity



Slow Memory

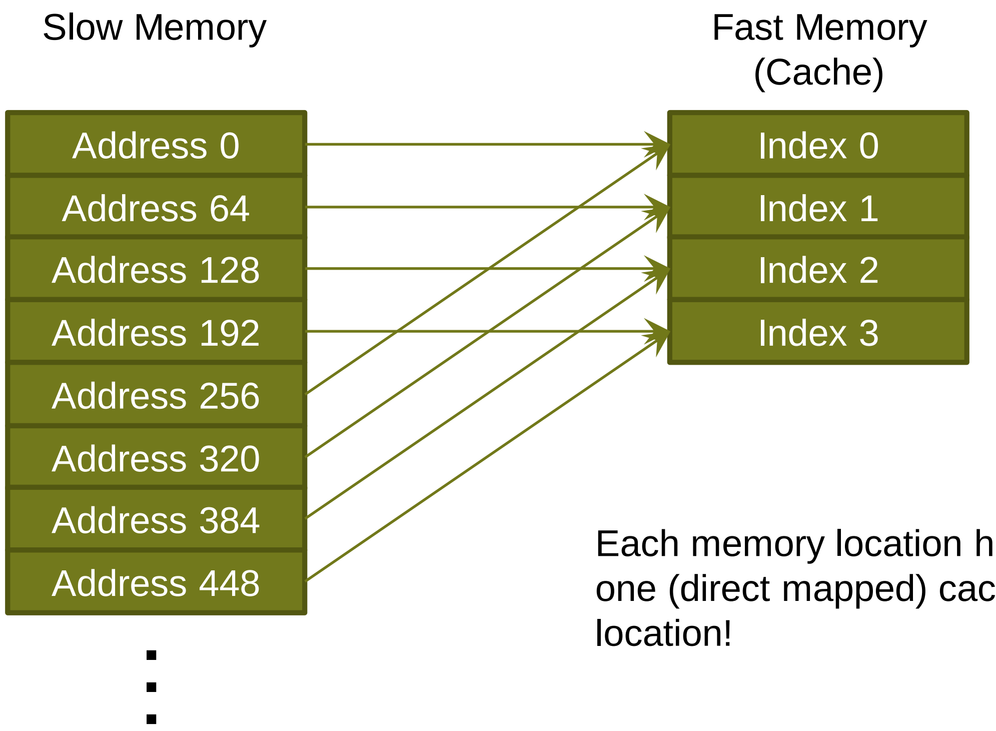
Address 0
Address 64
Address 128
Address 192
Address 256
Address 320
Address 384
Address 448
⋮

Fast Memory
(Cache)

Index 0, Way 0
Index 0, Way 1
Index 1, Way 0
Index 1, Way 1

Cache Structure

Simplest design: direct mapped!



Slow Memory

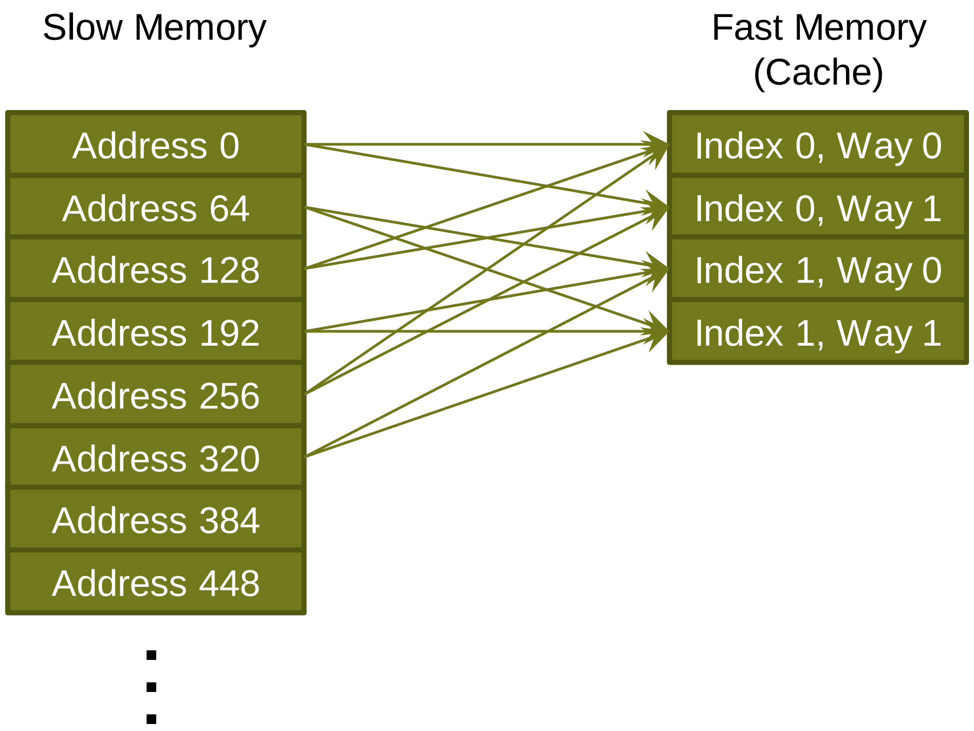
Fast Memory
(Cache)

Address 0
Address 64
Address 128
Address 192
Address 256
Address 320
Address 384
Address 448
⋮

Index 0
Index 1
Index 2
Index 3

Each memory location has one (direct mapped) cache location!

Adding 2-way associativity



Slow Memory

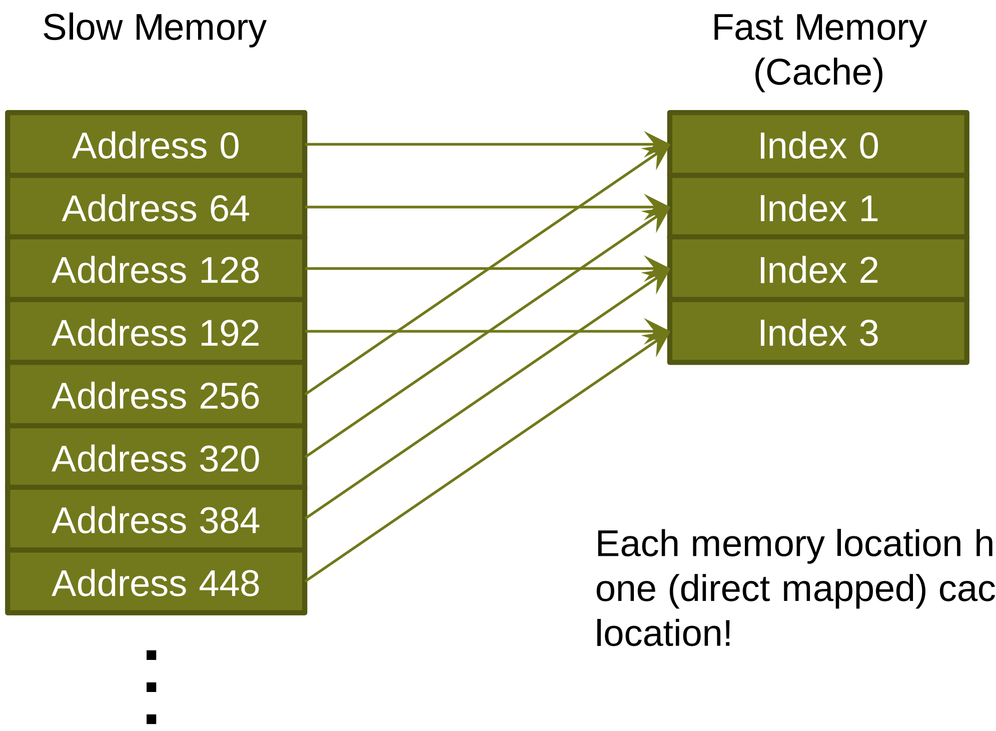
Fast Memory
(Cache)

Address 0
Address 64
Address 128
Address 192
Address 256
Address 320
Address 384
Address 448
⋮

Index 0, Way 0
Index 0, Way 1
Index 1, Way 0
Index 1, Way 1

Cache Structure

Simplest design: direct mapped!

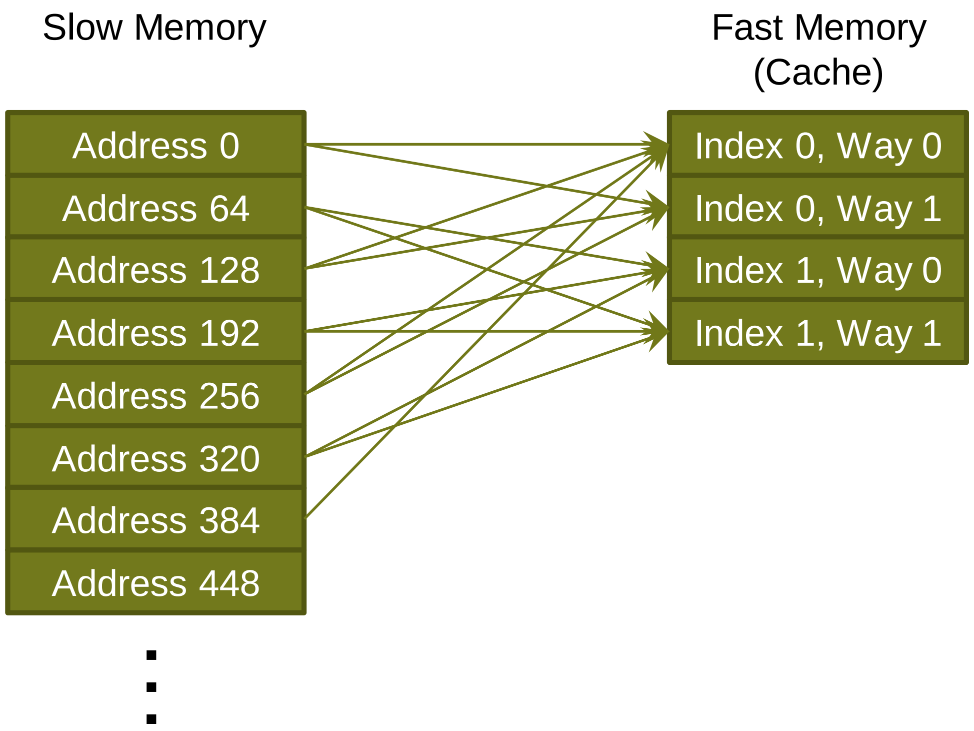


Slow Memory

Fast Memory (Cache)

Each memory location has one (direct mapped) cache location!

Adding 2-way associativity



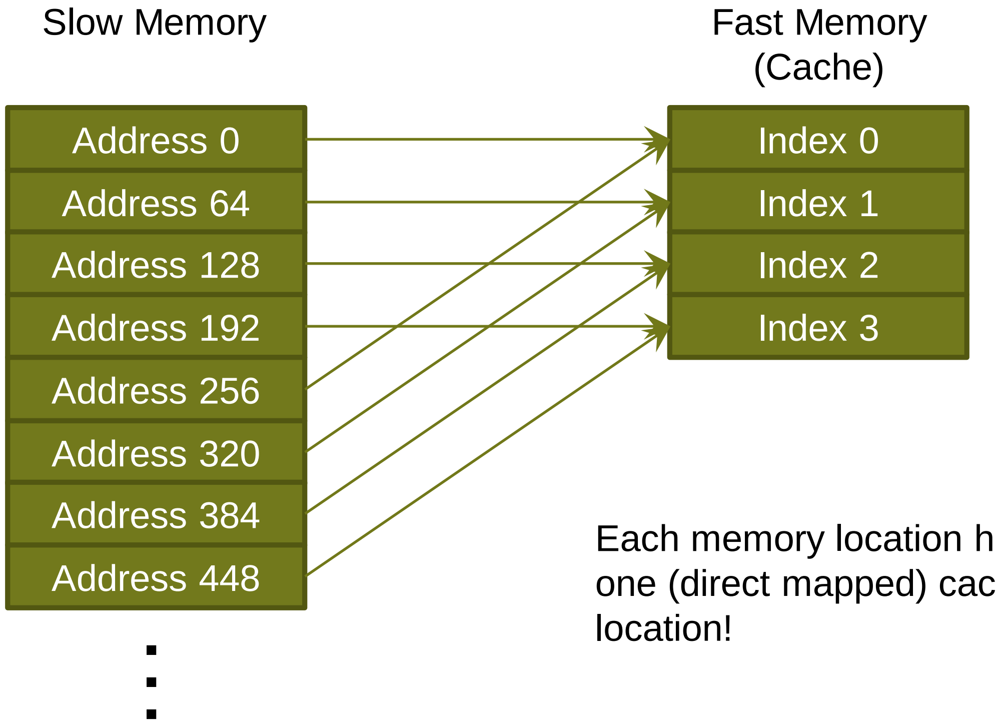
Slow Memory

Fast Memory (Cache)

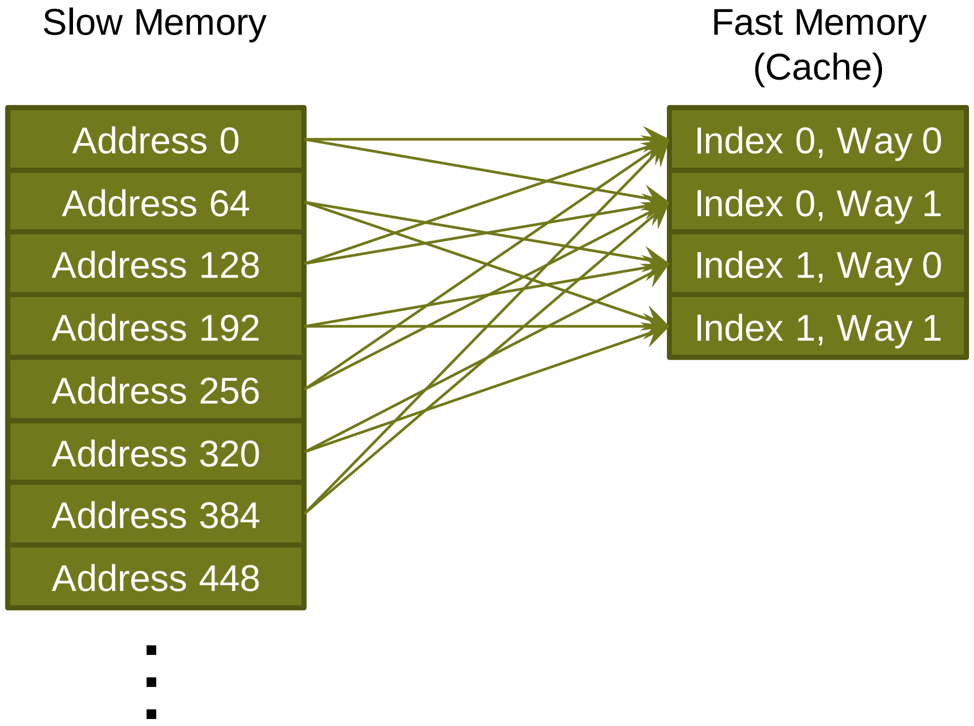
Cache Structure

Simplest design: direct mapped!

Adding 2-way associativity



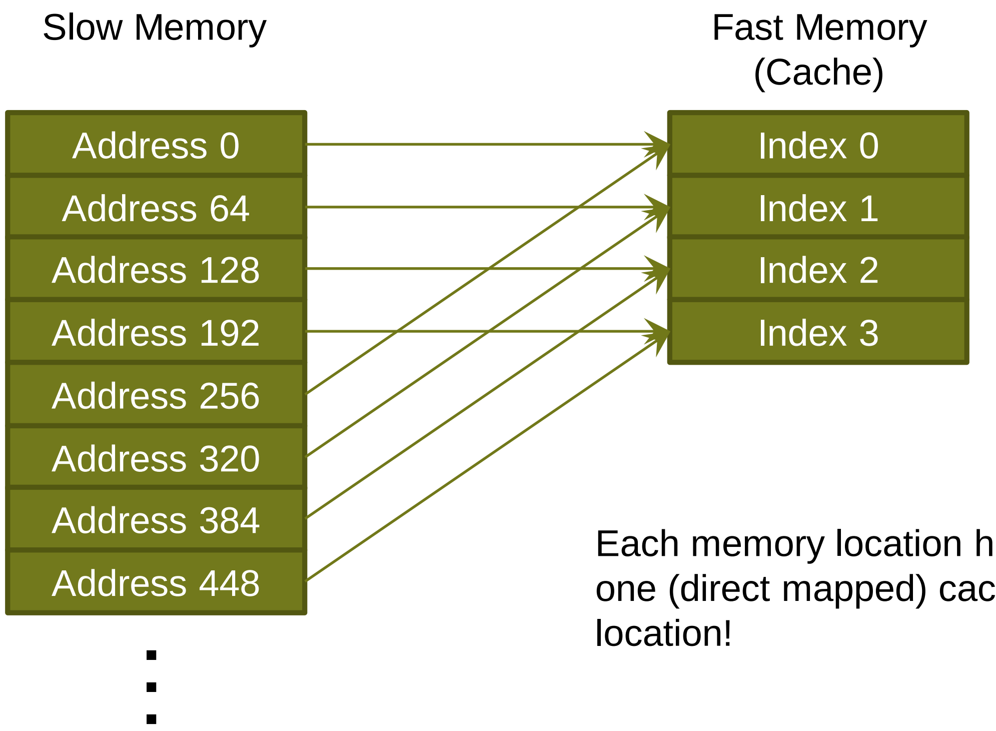
Each memory location has one (direct mapped) cache location!



Cache Structure

Simplest design: direct mapped!

Adding 2-way associativity



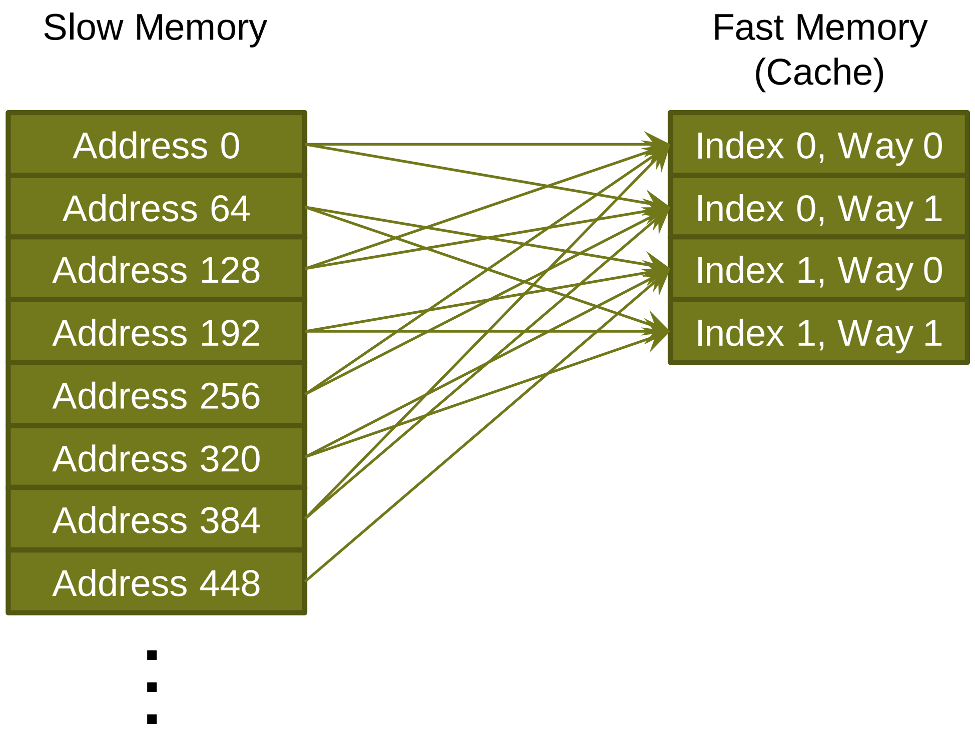
Slow Memory

Fast Memory (Cache)

Address 0
Address 64
Address 128
Address 192
Address 256
Address 320
Address 384
Address 448
⋮

Index 0
Index 1
Index 2
Index 3

Each memory location has one (direct mapped) cache location!



Slow Memory

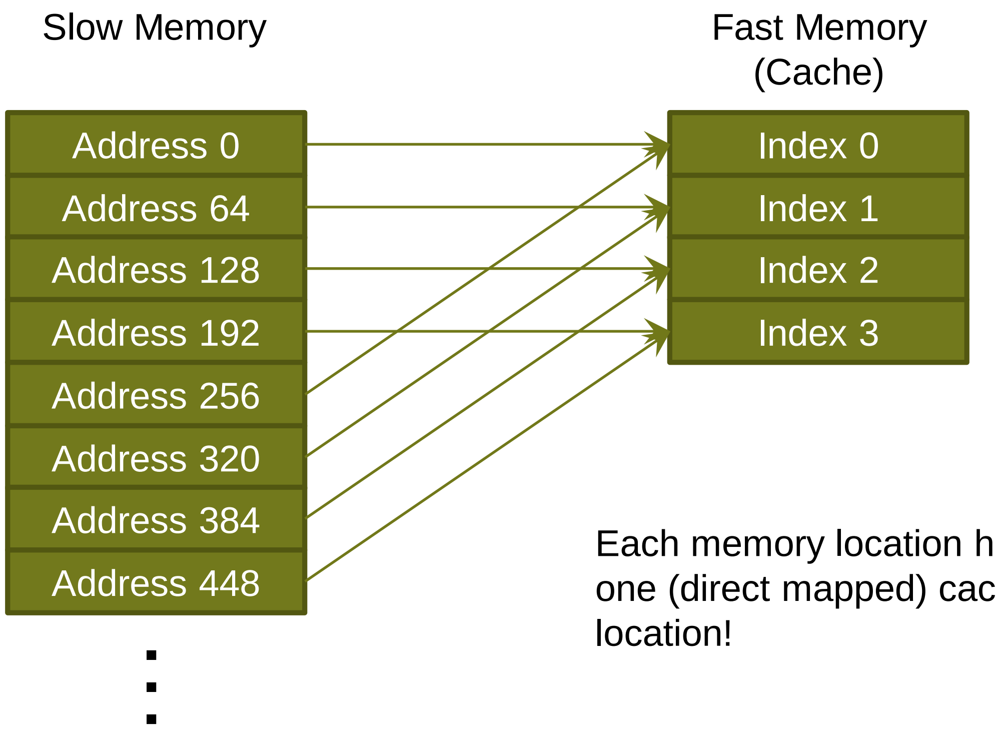
Fast Memory (Cache)

Address 0
Address 64
Address 128
Address 192
Address 256
Address 320
Address 384
Address 448
⋮

Index 0, Way 0
Index 0, Way 1
Index 1, Way 0
Index 1, Way 1

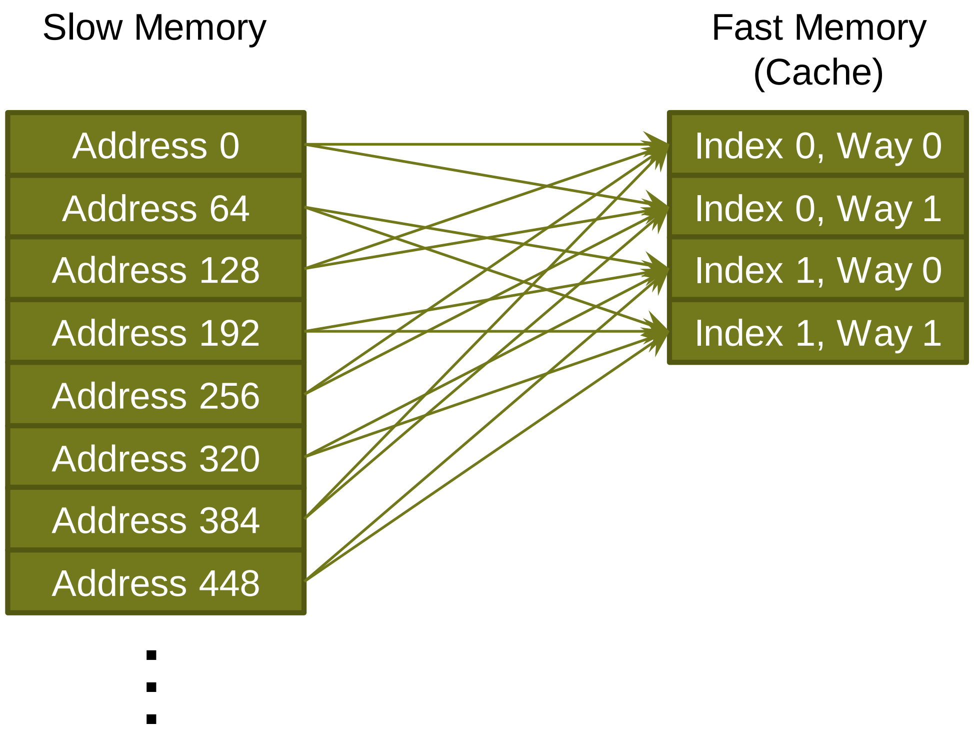
Cache Structure

Simplest design: direct mapped!



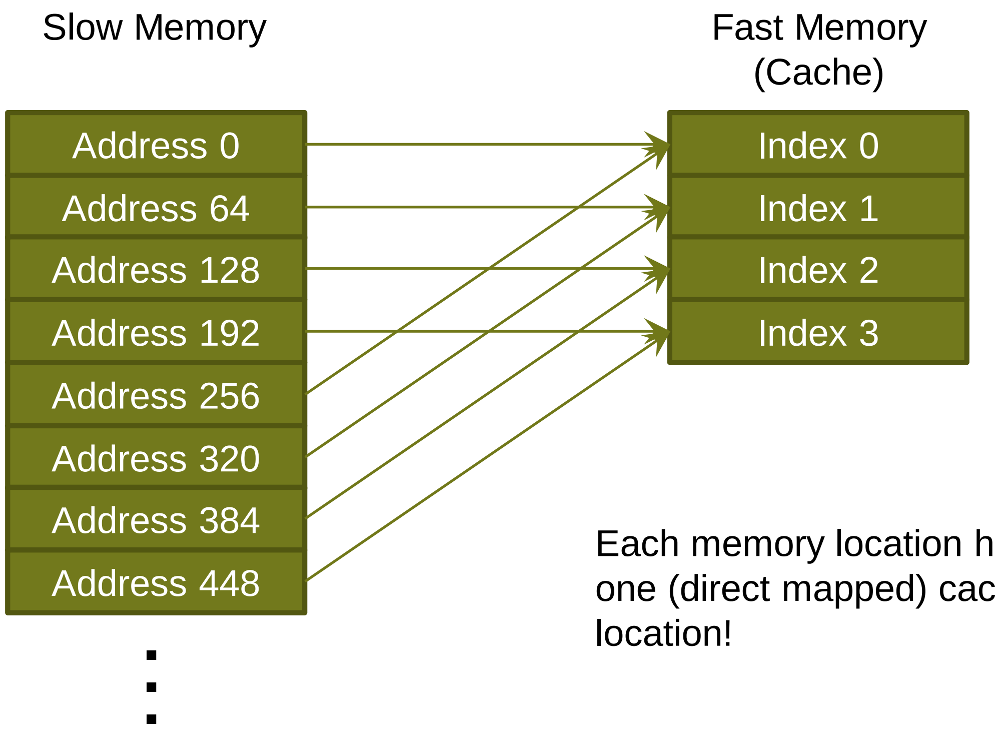
Each memory location has one (direct mapped) cache location!

Adding 2-way associativity



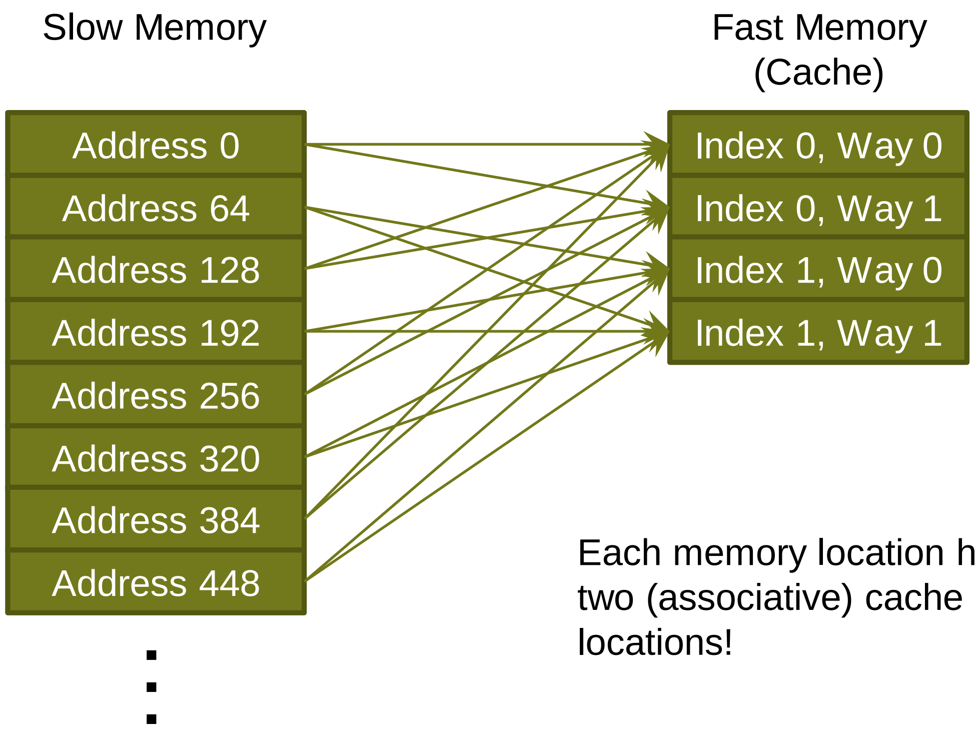
Cache Structure

Simplest design: direct mapped!



Each memory location has one (direct mapped) cache location!

Adding 2-way associativity



Each memory location has two (associative) cache locations!

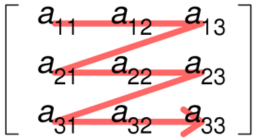
Example (S=4, E=2)

Ignore the variables sum, i, j

```
int sum_array_rows(double a[8][8])
{
  int i, j;
  double sum = 0;

  for (i = 0; i < 8; i++)
    for (j = 0; j < 8; j++)
      sum += a[i][j];
  return sum;
}
```

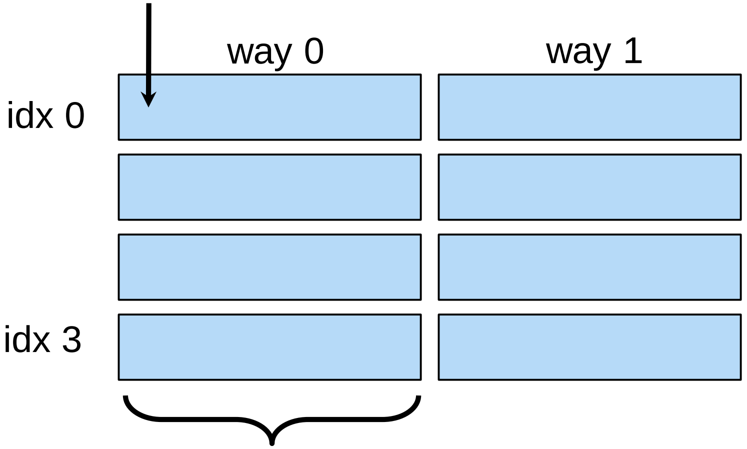
```
int sum_array_cols(double a[8][8])
{
  int i, j;
  double sum = 0;

  for (j = 0; j < 8; i++)
    for (i = 0; i < 8; j++)
      sum += a[i][j];
  return sum;
}
```

Row-major order


a_{11} a_{12} a_{13}
a_{21} a_{22} a_{23}
a_{31} a_{32} a_{33}

C/C++ uses row-major
(image source:Wikipedia)

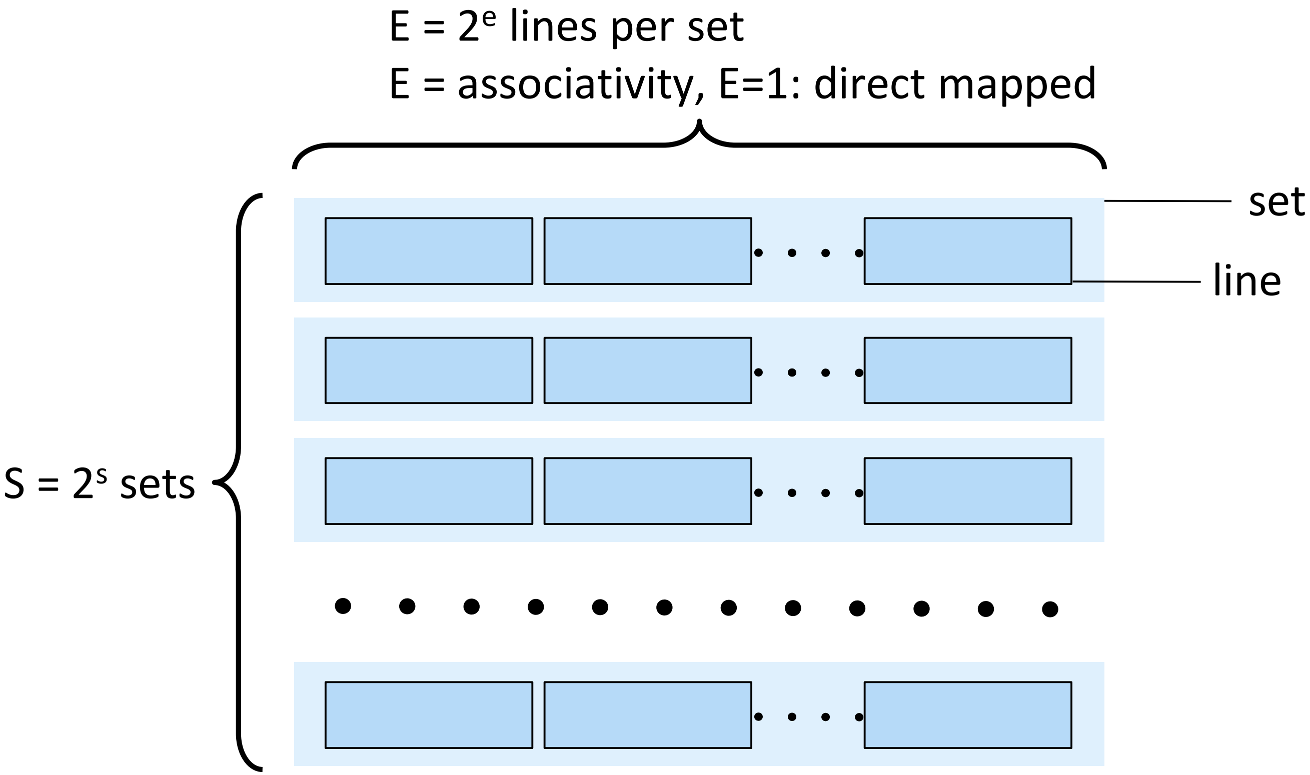
assume: cold (empty) cache, a[0][0] goes here



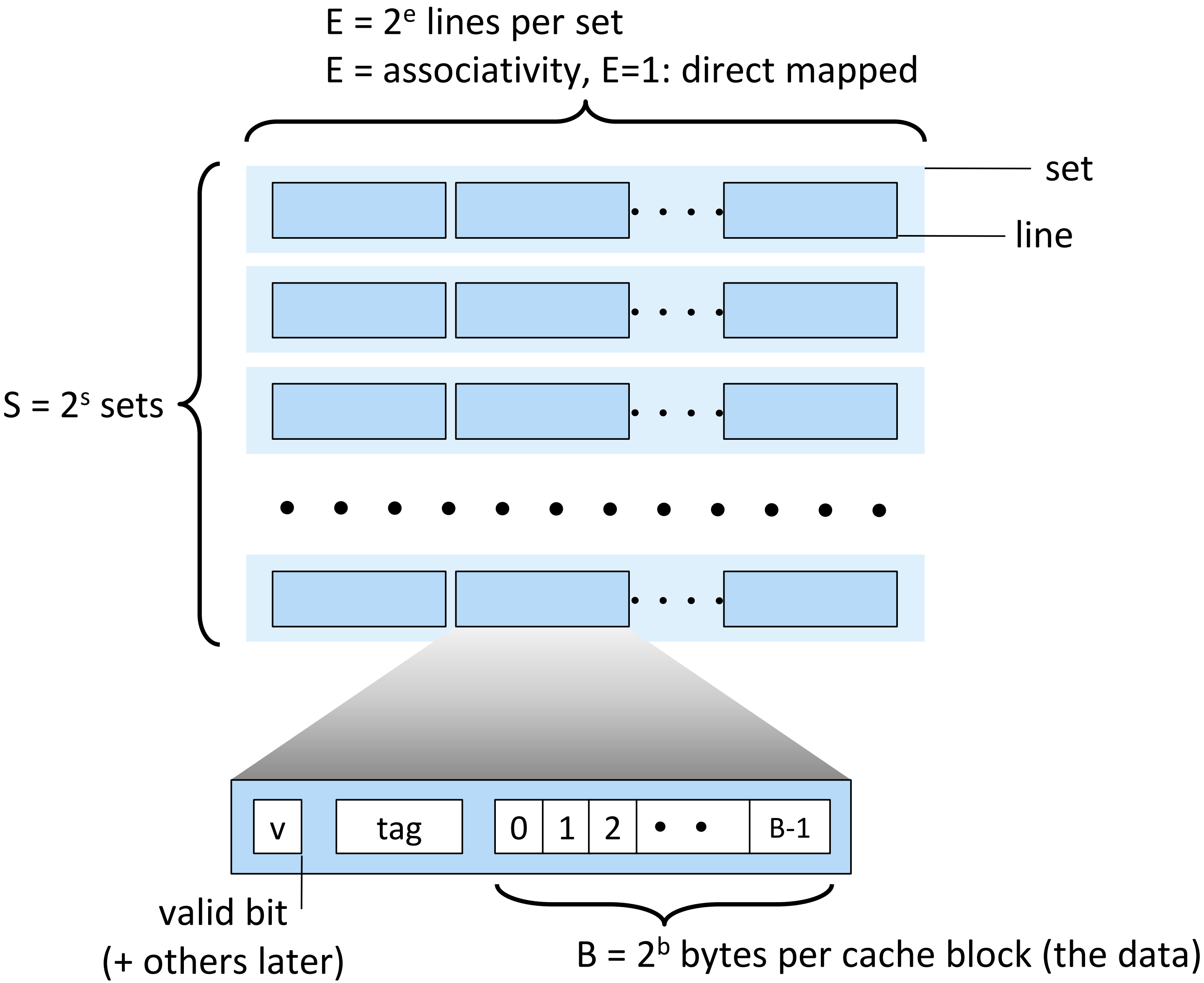
B = 32 byte = 4 doubles

blackboard

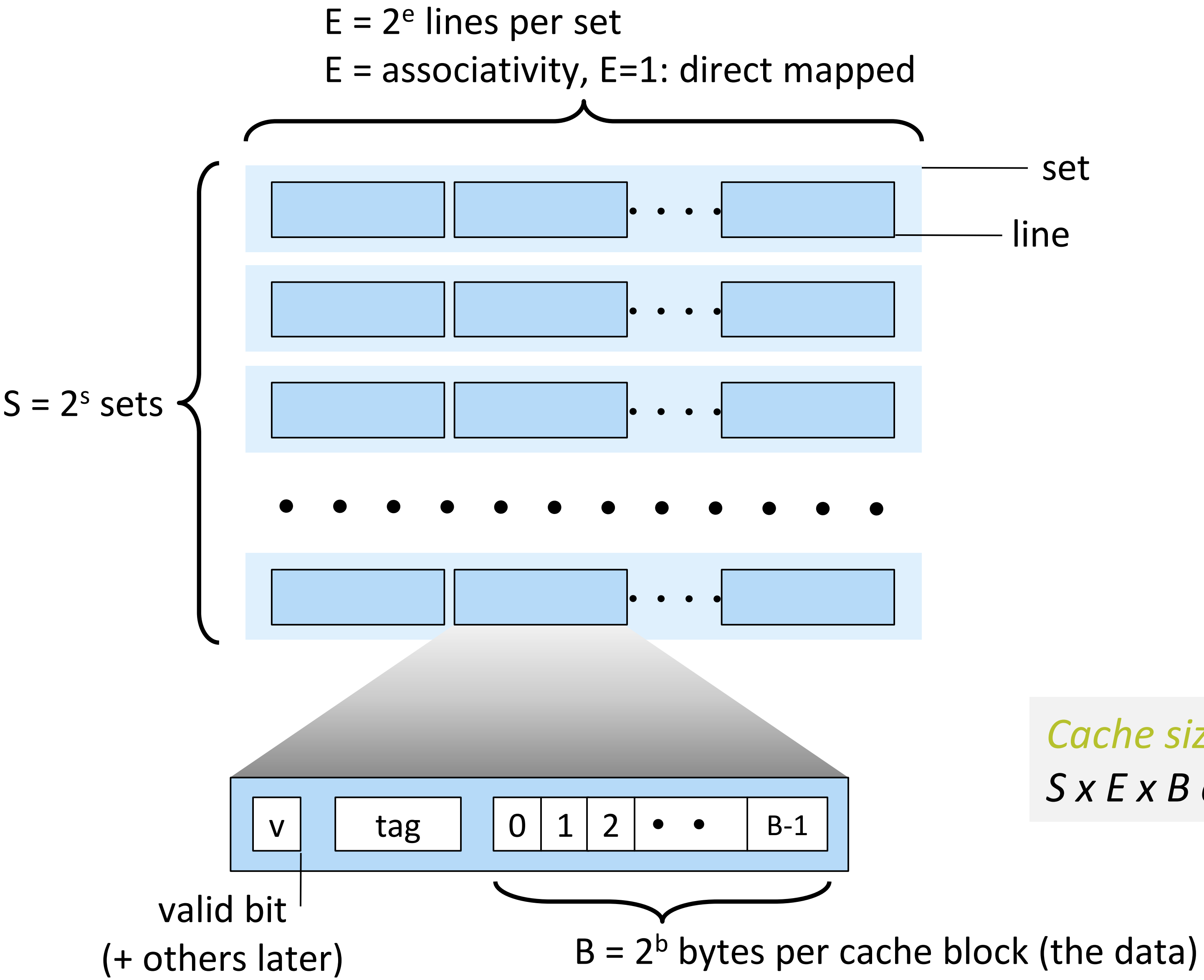
General Cache Organization (S, E, B)



General Cache Organization (S, E, B)

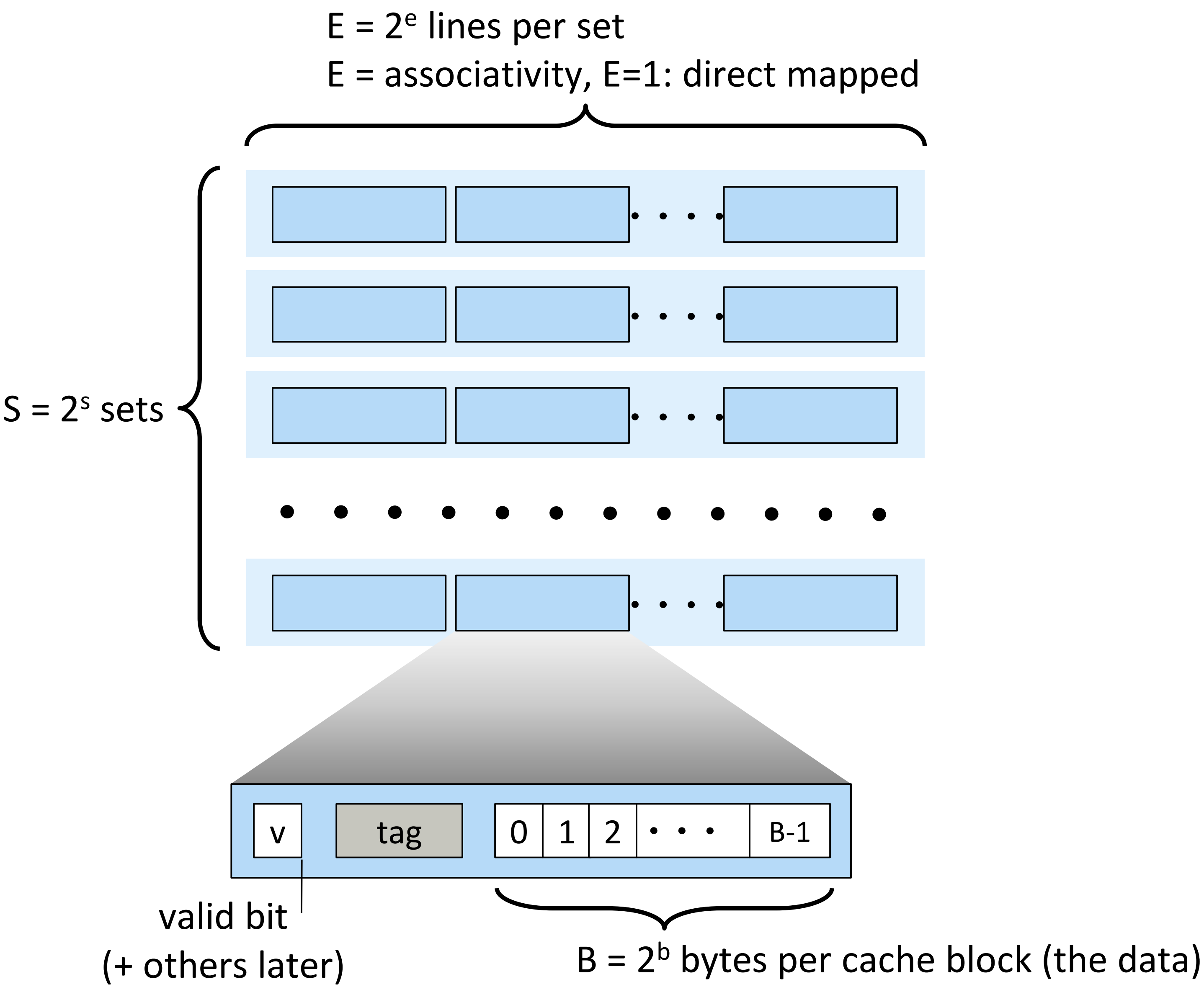

E = 2^e lines per set
E = associativity, E=1: direct mapped
set
line
S = 2^s sets
v
tag
0
1
2
B-1
valid bit
(+ others later)
B = 2^b bytes per cache block (the data)

General Cache Organization (S, E, B)

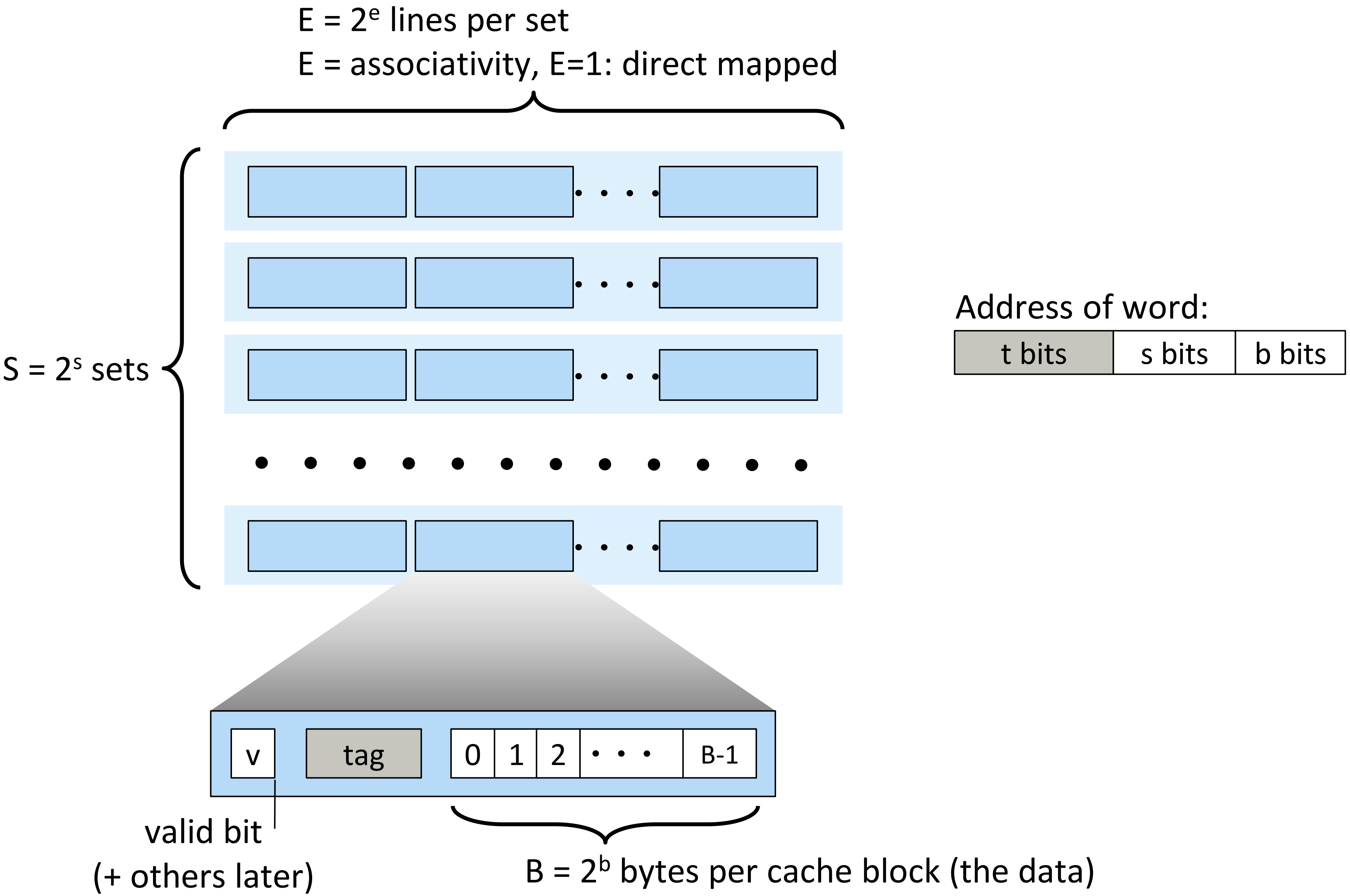


Cache size:
S x E x B data bytes

Cache Read

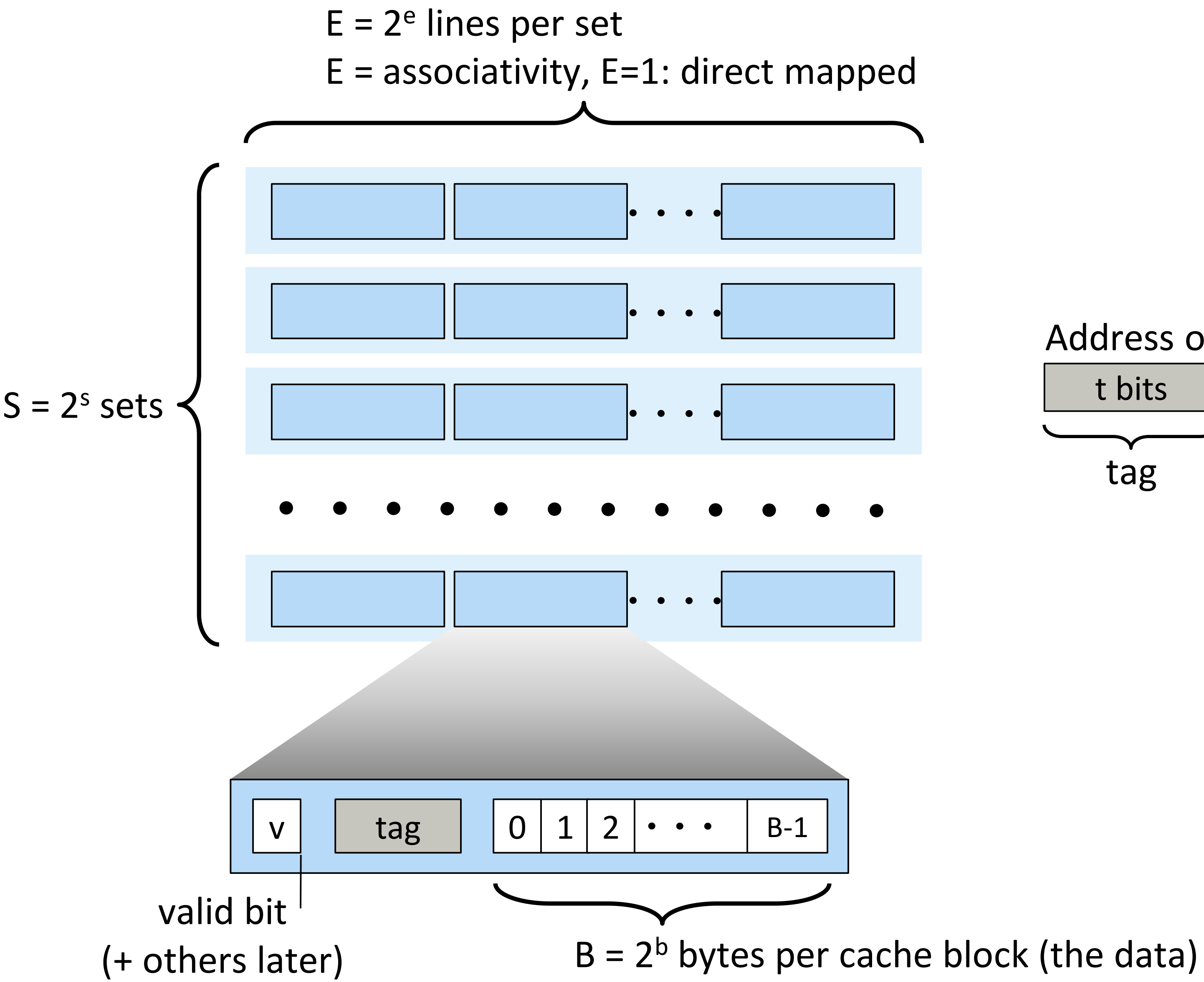

E = 2^e lines per set
E = associativity, E=1: direct mapped
S = 2^s sets
v
tag
0
1
2
B-1
valid bit
(+ others later)
B = 2^b bytes per cache block (the data)

Cache Read

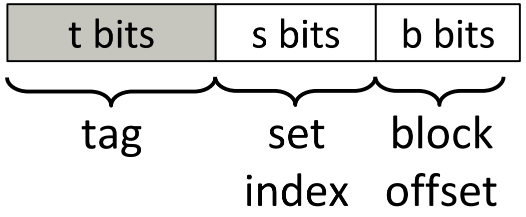


E = 2^e lines per set
E = associativity, E=1: direct mapped
S = 2^s sets
Address of word:
t bits
s bits
b bits
v
tag
0
1
2
• • •
B-1
valid bit
(+ others later)
B = 2^b bytes per cache block (the data)

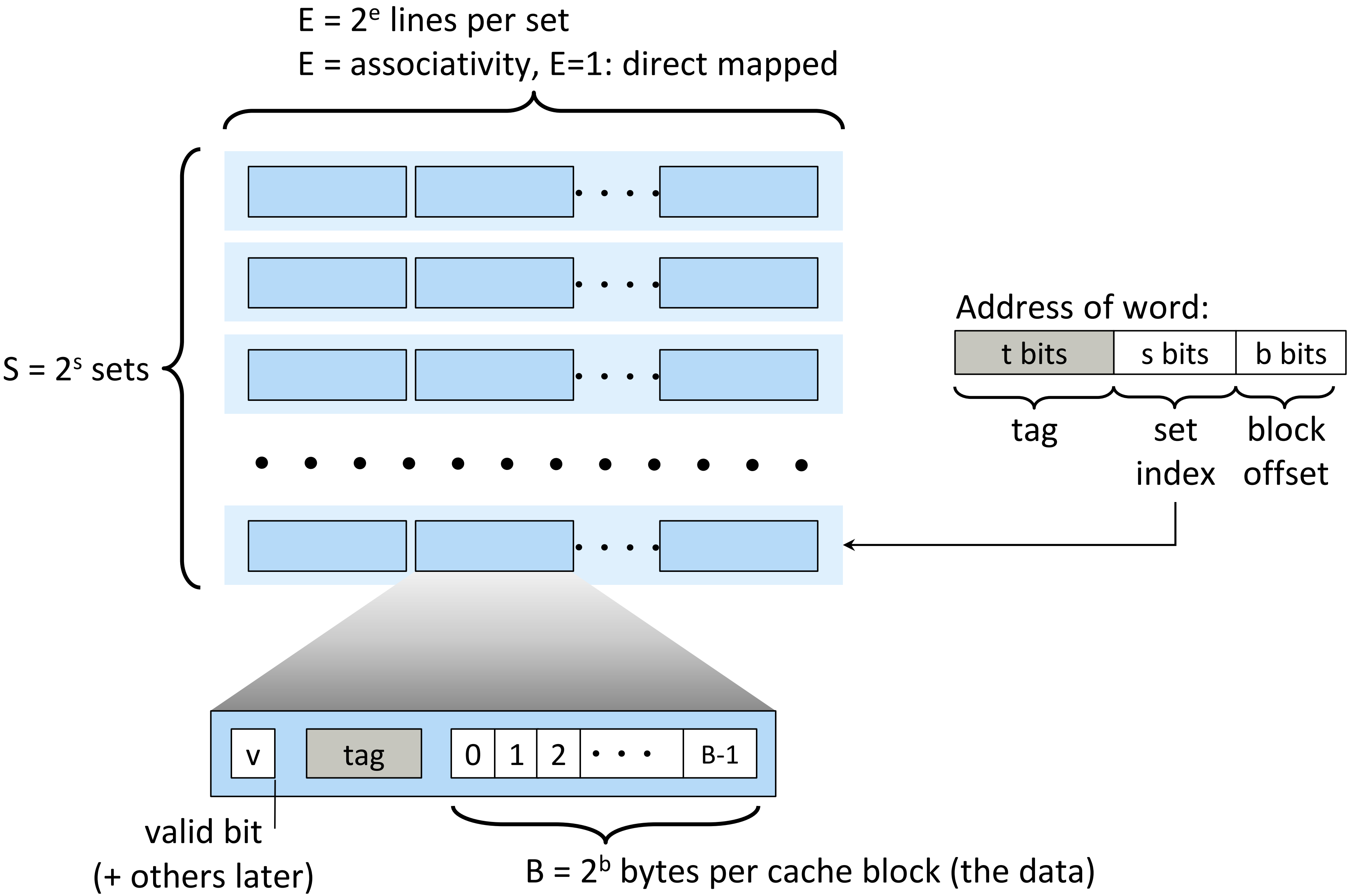
Cache Read


E = 2^e lines per set
E = associativity, E=1: direct mapped
S = 2^s sets
v
tag
0
1
2
• • •
B-1
valid bit
(+ others later)
B = 2^b bytes per cache block (the data)

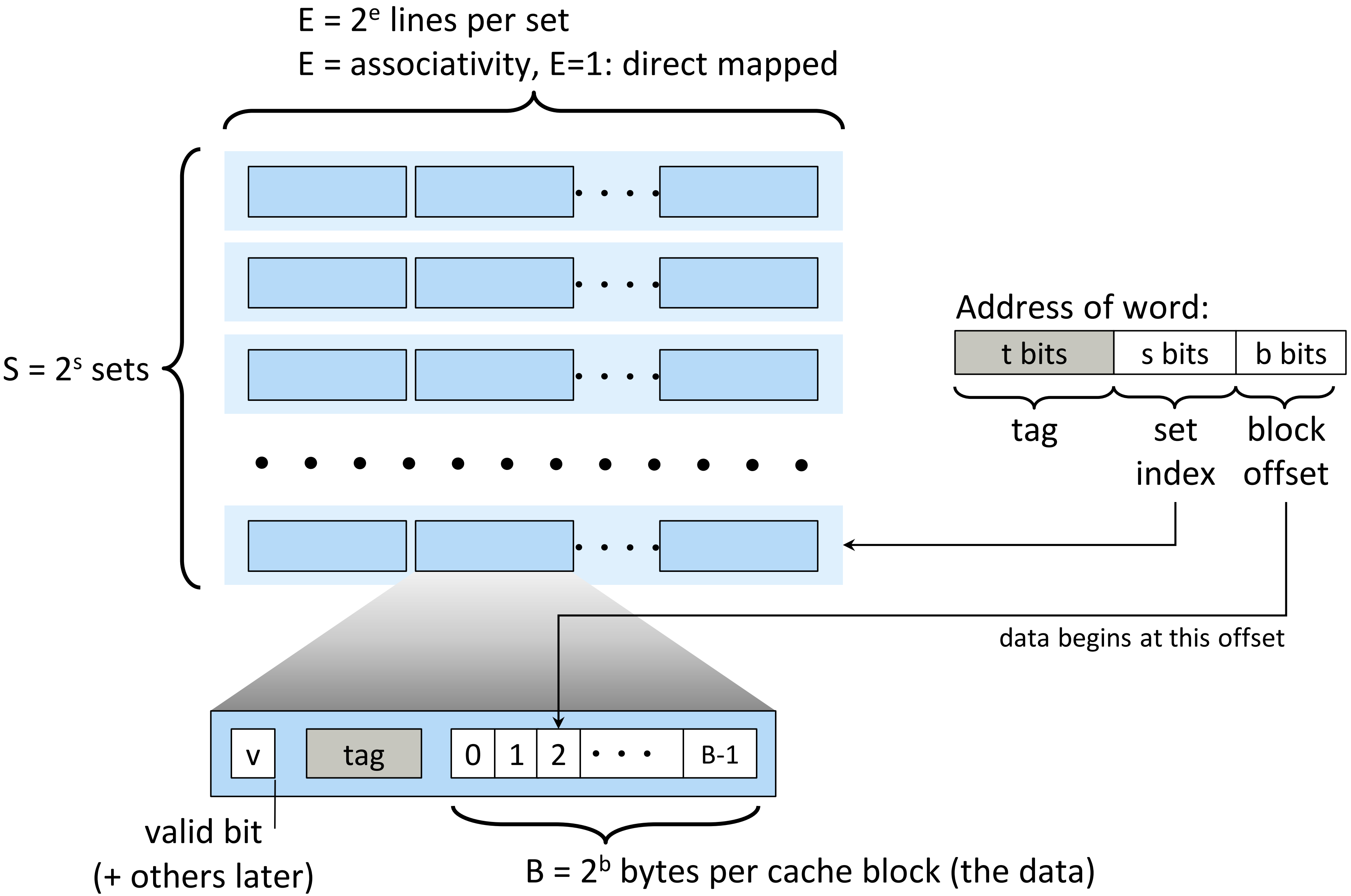
Address of word:



Cache Read

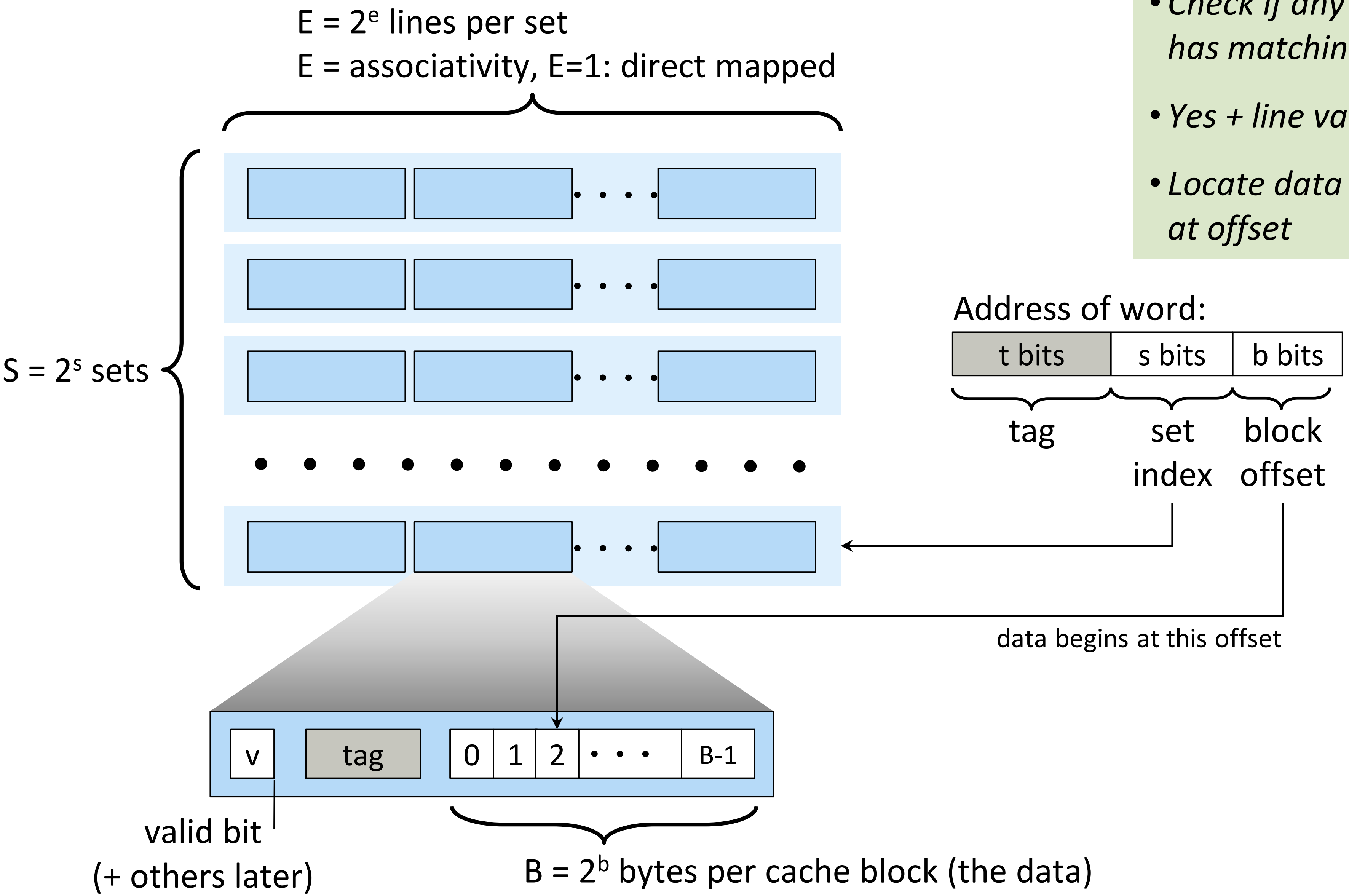

E = 2^e lines per set
E = associativity, E=1: direct mapped
S = 2^s sets
Address of word:
t bits
s bits
b bits
tag
set index
block offset
v
tag
0
1
2
• • •
B-1
valid bit (+ others later)
B = 2^b bytes per cache block (the data)

Cache Read


E = 2^e lines per set
E = associativity, E=1: direct mapped
S = 2^s sets
Address of word:
t bits
s bits
b bits
tag
set index
block offset
data begins at this offset
v
tag
0
1
2
• • •
B-1
valid bit
(+ others later)
B = 2^b bytes per cache block (the data)

Cache Read

- *Locate set*
- *Check if any line in set has matching tag*
- *Yes + line valid: hit*
- *Locate data starting at offset*



Terminology

- **Direct mapped cache:**
  - Cache with E = 1
  - Means every block from memory has a unique location in cache
- **Fully associative cache**
  - Cache with S = 1 (i.e., maximal E)
  - Means every block from memory can be mapped to any location in cache
  - In practice to expensive to build
  - One can view the register file as a fully associative cache
- **LRU (least recently used) replacement**
  - when selecting which block should be replaced (happens only for E > 1), the least recently used one is chosen

Types of Cache Misses (The 3 C's)

- ***Compulsory (cold)* miss**

  Occurs on first access to a block
- ***Capacity* miss**

  Occurs when working set is larger than the cache
- ***Conflict* miss**

  Conflict misses occur when the cache is large enough, but multiple data objects all map to the same slot

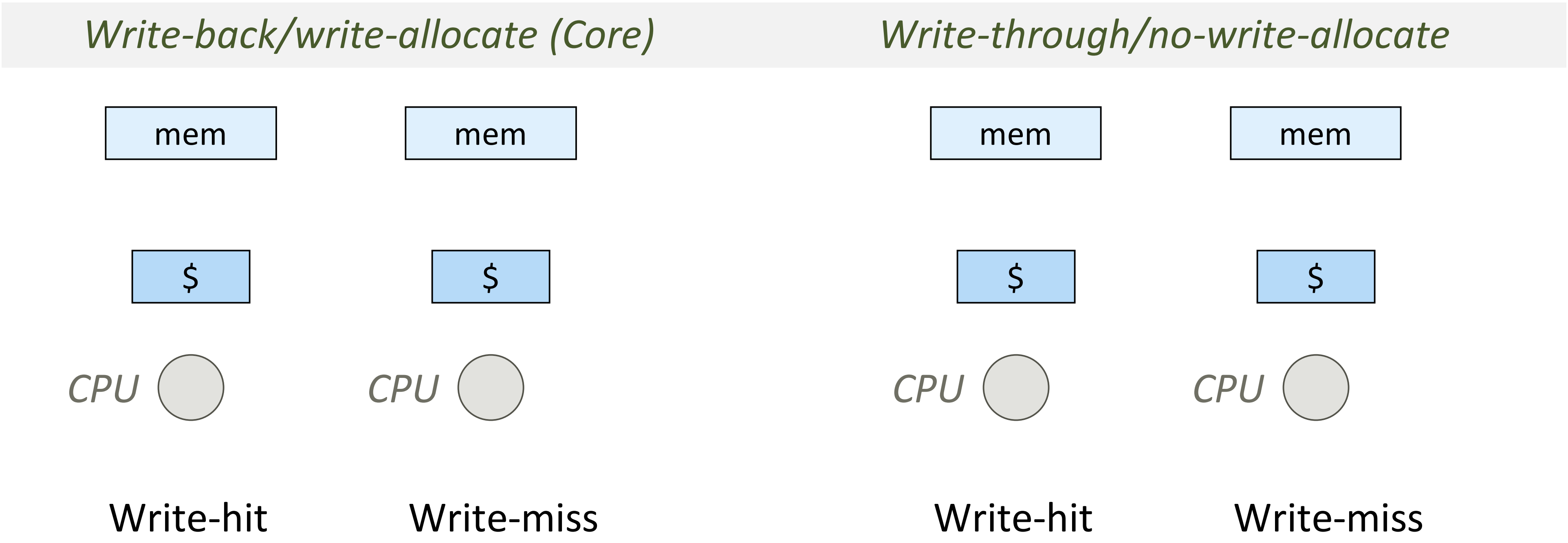
- **Not a clean classification but still useful**

What about writes?

- **What to do on a write-hit?**
  - ***Write-through:*** write immediately to memory
  - ***Write-back:*** defer write to memory until replacement of line
- **What to do on a write-miss?**
  - ***Write-allocate:*** load into cache, update line in cache
  - ***No-write-allocate:*** writes immediately to memory

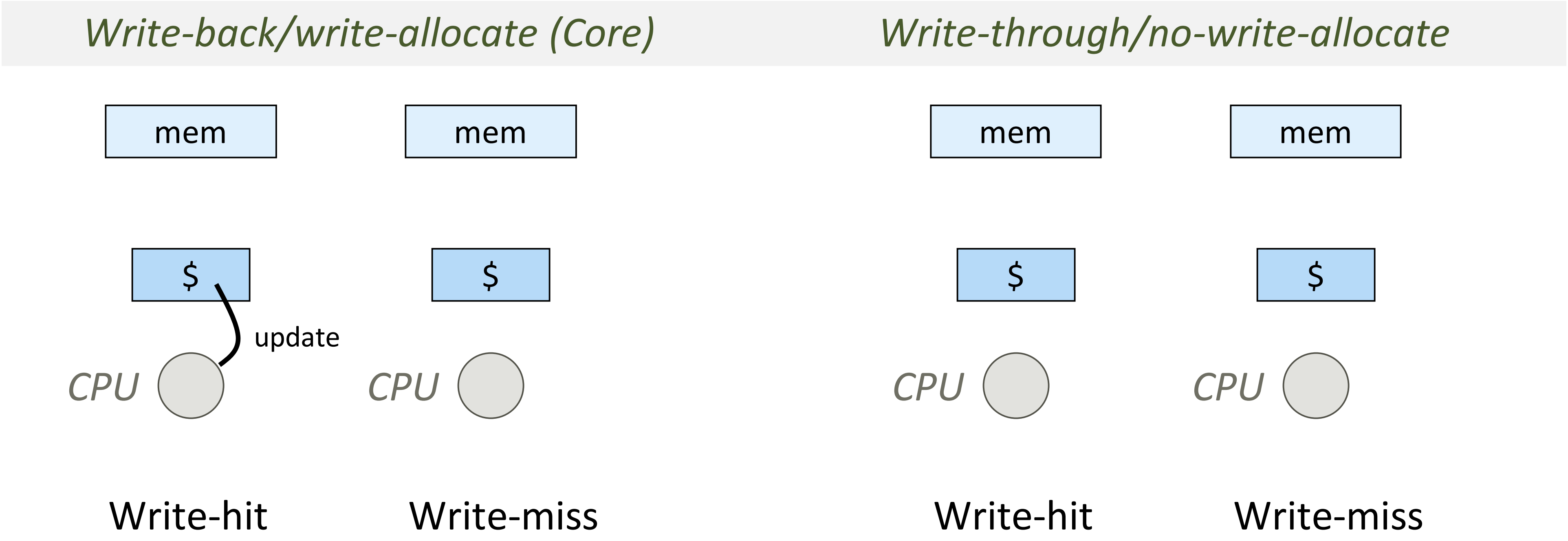
What about writes?

- **What to do on a write-hit?**
  - ***Write-through:*** write immediately to memory
  - ***Write-back:*** defer write to memory until replacement of line
- **What to do on a write-miss?**
  - ***Write-allocate:*** load into cache, update line in cache
  - ***No-write-allocate:*** writes immediately to memory



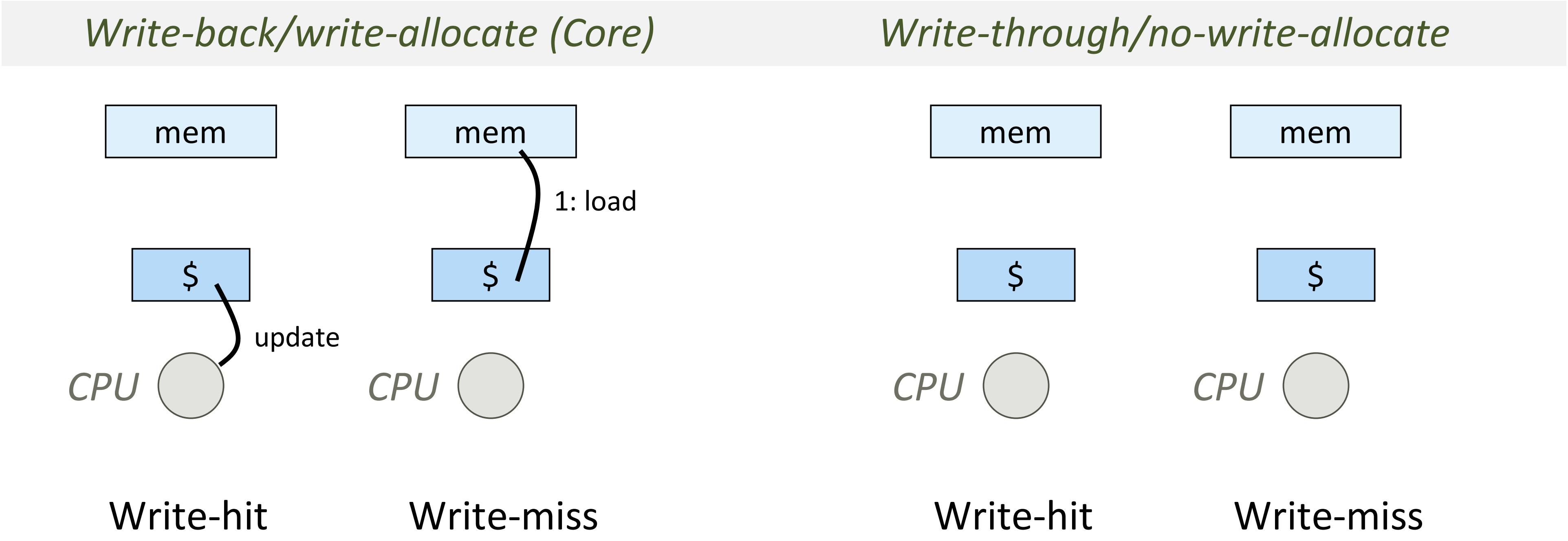
What about writes?

- **What to do on a write-hit?**
  - ***Write-through:*** write immediately to memory
  - ***Write-back:*** defer write to memory until replacement of line
- **What to do on a write-miss?**
  - ***Write-allocate:*** load into cache, update line in cache
  - ***No-write-allocate:*** writes immediately to memory



What about writes?

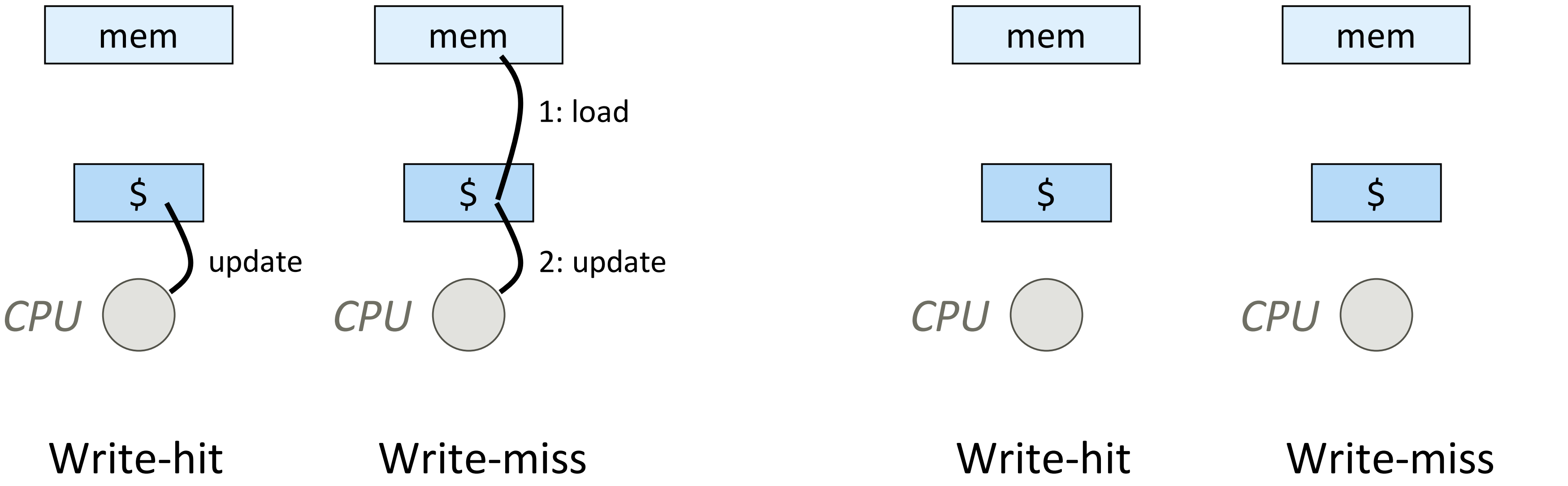
- **What to do on a write-hit?**
  - ***Write-through:*** write immediately to memory
  - ***Write-back:*** defer write to memory until replacement of line
- **What to do on a write-miss?**
  - ***Write-allocate:*** load into cache, update line in cache
  - ***No-write-allocate:*** writes immediately to memory



What about writes?

- **What to do on a write-hit?**
  - ***Write-through:*** write immediately to memory
  - ***Write-back:*** defer write to memory until replacement of line
- **What to do on a write-miss?**
  - ***Write-allocate:*** load into cache, update line in cache
  - ***No-write-allocate:*** writes immediately to memory

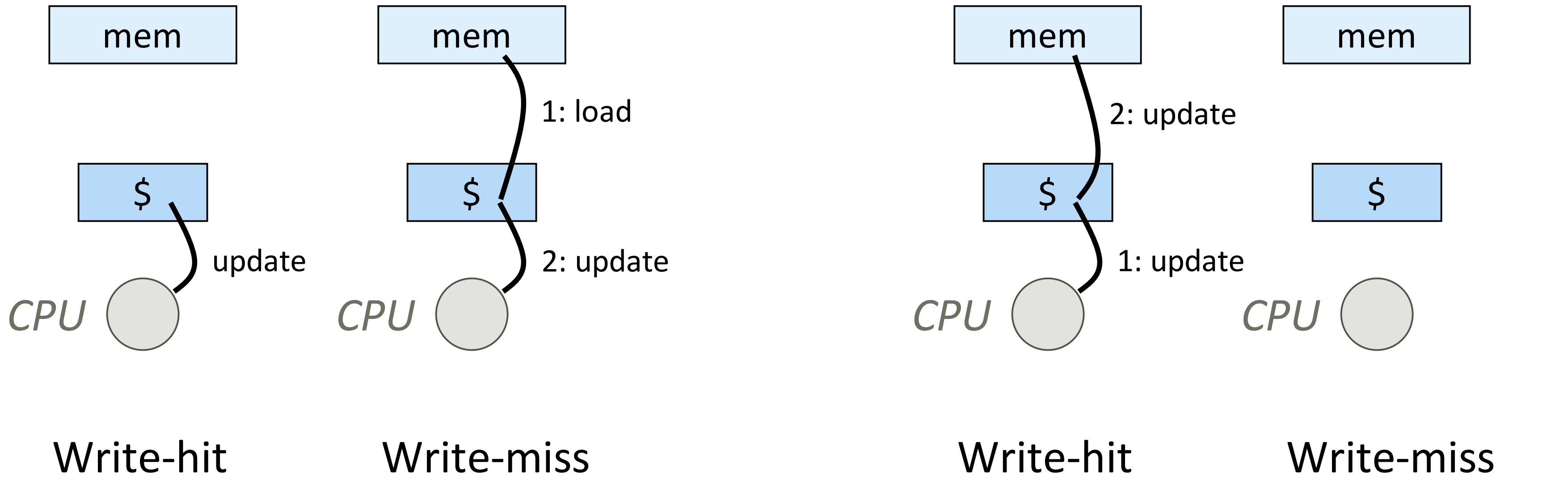
Write-back/write-allocate (Core) *Write-through/no-write-allocate*



What about writes?

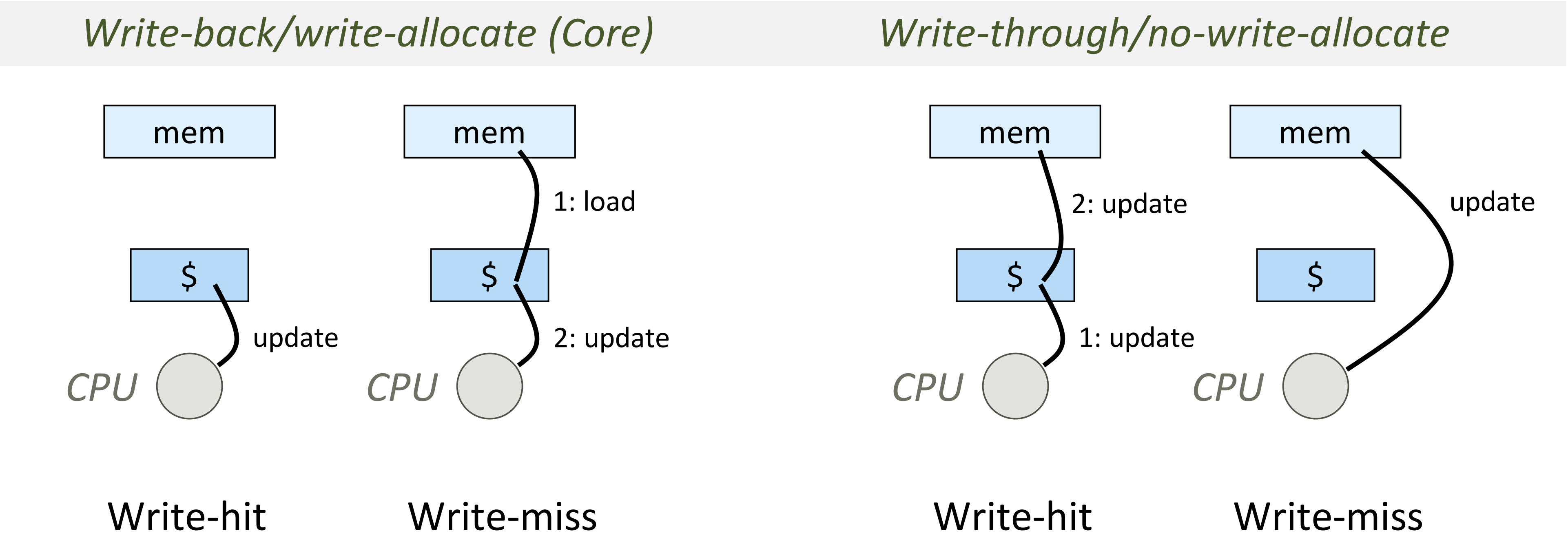
- **What to do on a write-hit?**
  - ***Write-through:*** write immediately to memory
  - ***Write-back:*** defer write to memory until replacement of line
- **What to do on a write-miss?**
  - ***Write-allocate:*** load into cache, update line in cache
  - ***No-write-allocate:*** writes immediately to memory

Write-back/write-allocate (Core) *Write-through/no-write-allocate*



What about writes?

- **What to do on a write-hit?**
  - ***Write-through:*** write immediately to memory
  - ***Write-back:*** defer write to memory until replacement of line
- **What to do on a write-miss?**
  - ***Write-allocate:*** load into cache, update line in cache
  - ***No-write-allocate:*** writes immediately to memory

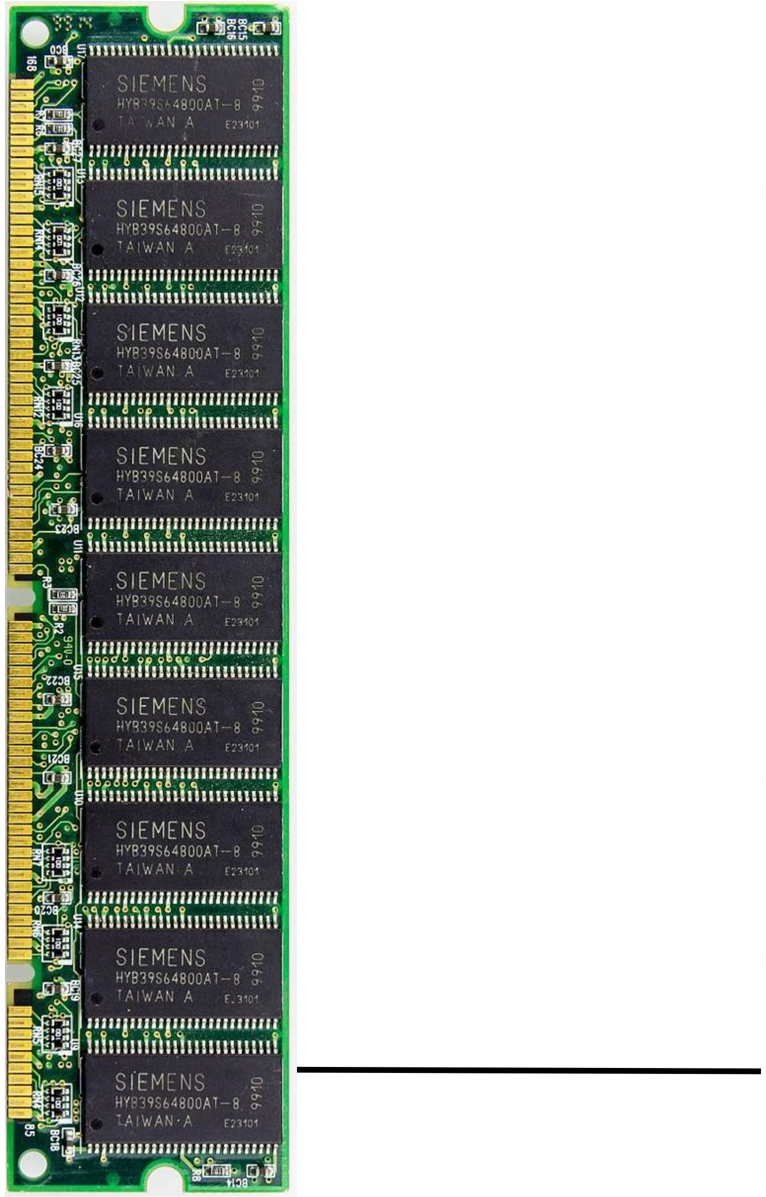


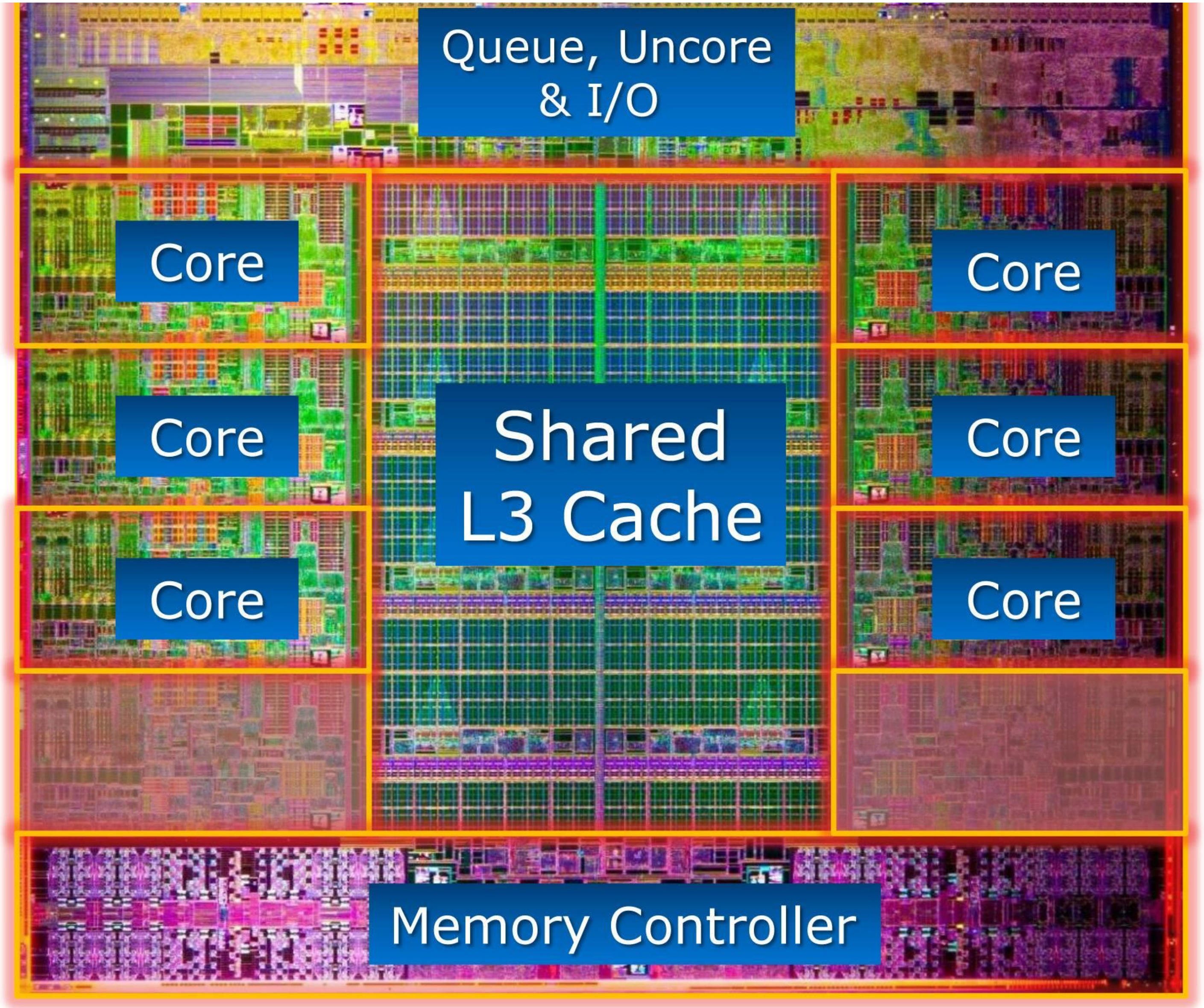
The actual topic: Cache Coherence in Multiprocessors

- **Different caches may have a copy of the same memory location!**
- **Cache coherence**
    - Manages existence of multiple copies
- **Cache architectures**
    - Multi level caches
    - Shared vs. private (partitioned)
    - Inclusive vs. exclusive
    - Write back vs. write through
    - Victim cache to reduce conflict misses
    - …

Exclusive Hierarchical Caches

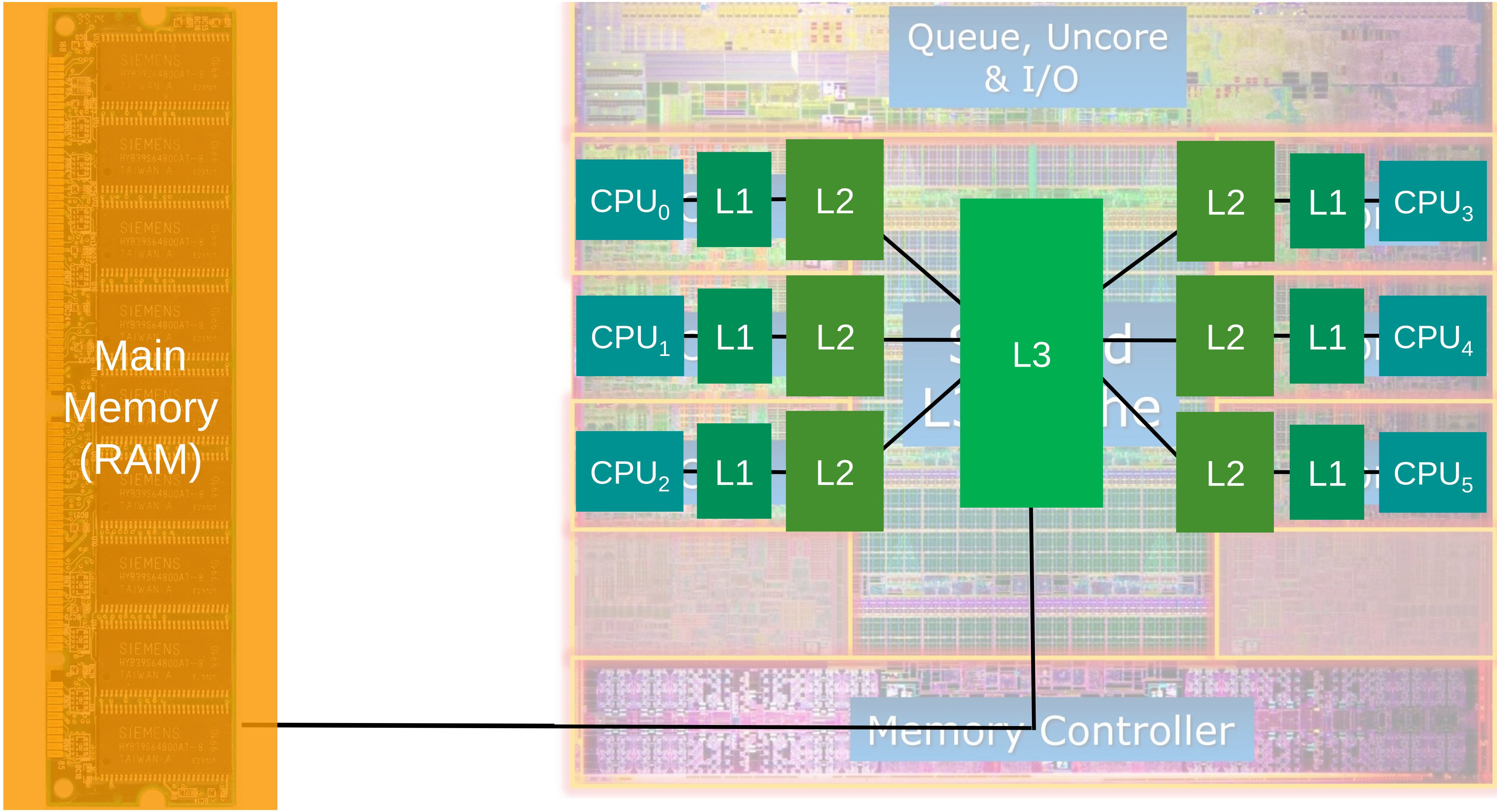
Example: Intel i7-3960X



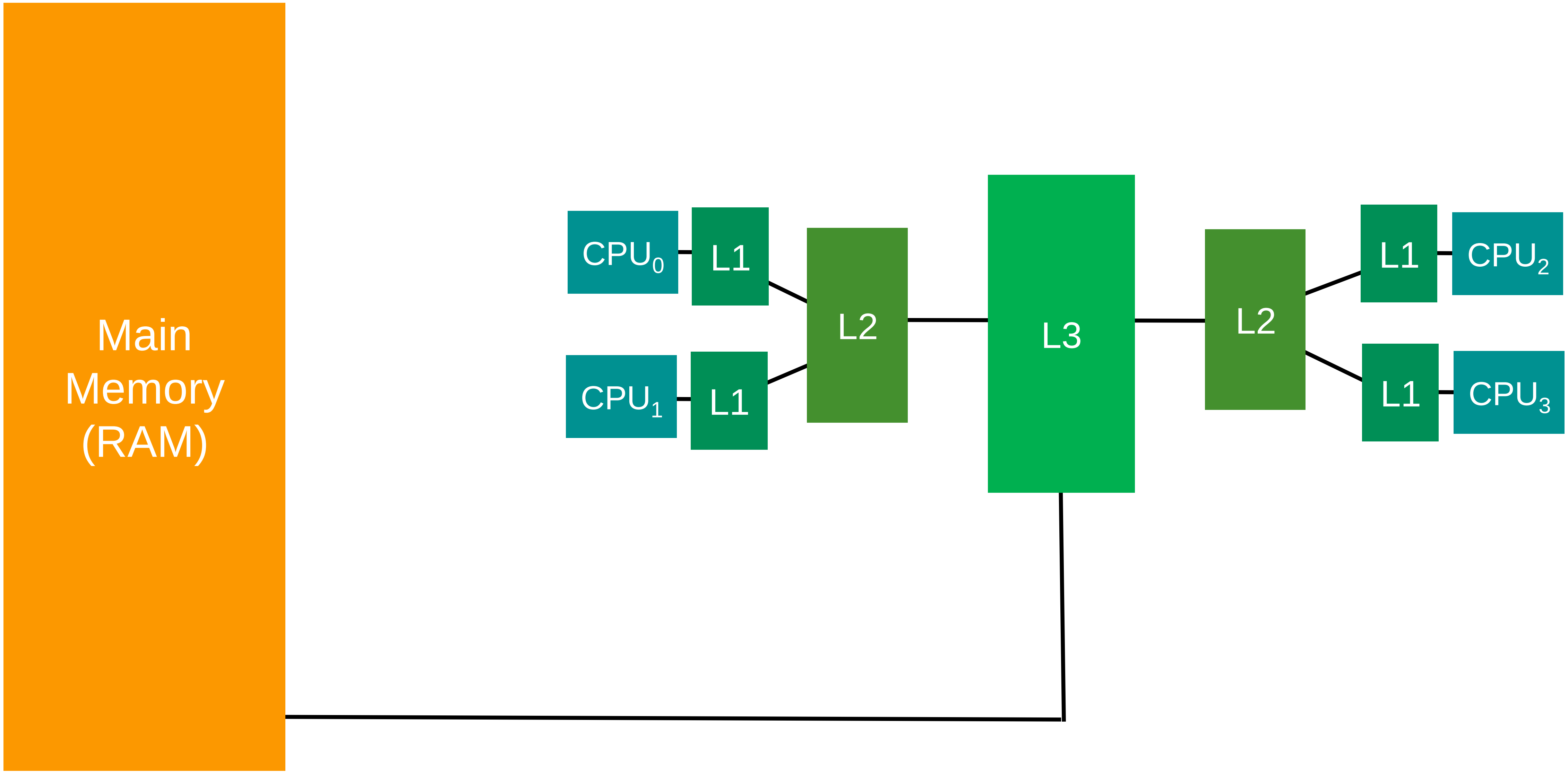


Exclusive Hierarchical Caches

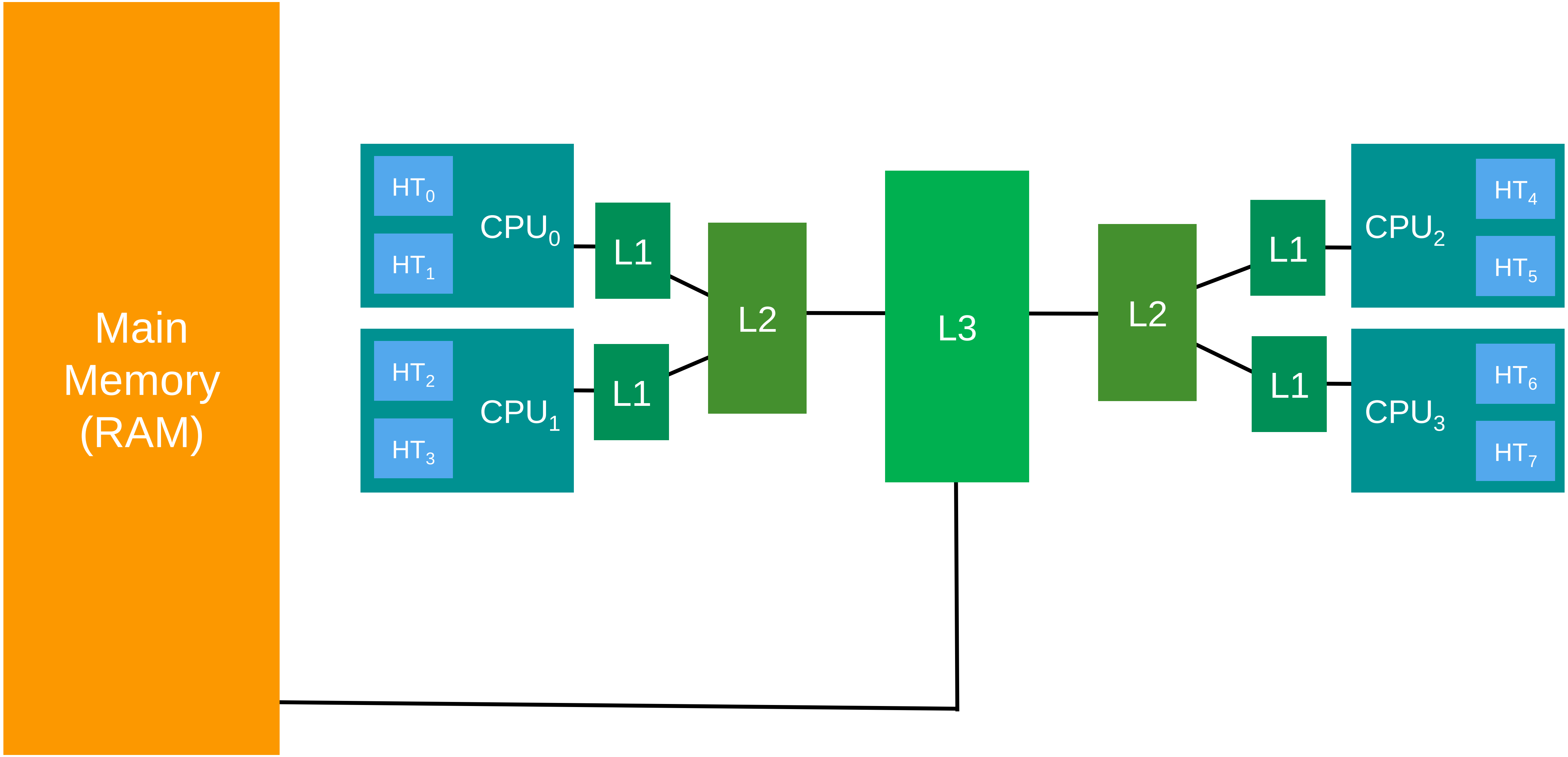
Example: Intel i7-3960X



Shared Hierarchical Caches



Shared Hierarchical Caches with MT



Caching Strategies (repeat)

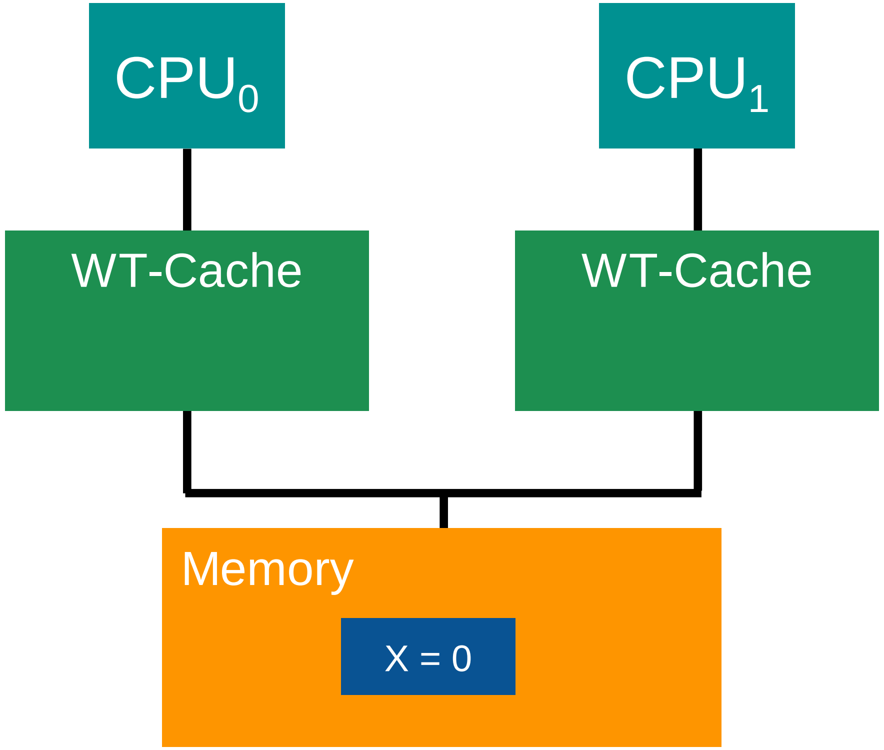
- **Remember:**
  - Write Back?
  - Write Through?

- **Cache coherence requirements**

  A memory system is coherent if it guarantees the following:
  - ***Write propagation*** (updates are eventually visible to all readers)
  - ***Write serialization*** (writes to the same location must be observed in order)

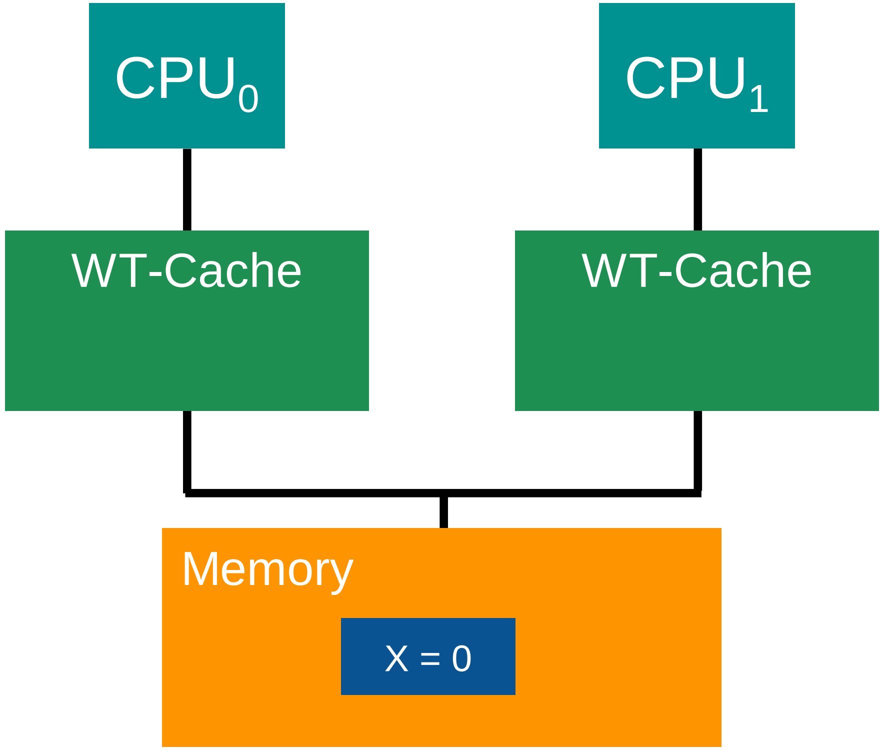
  Everything else: memory model issues (later)

Write Through Cache



Requires write propagation!

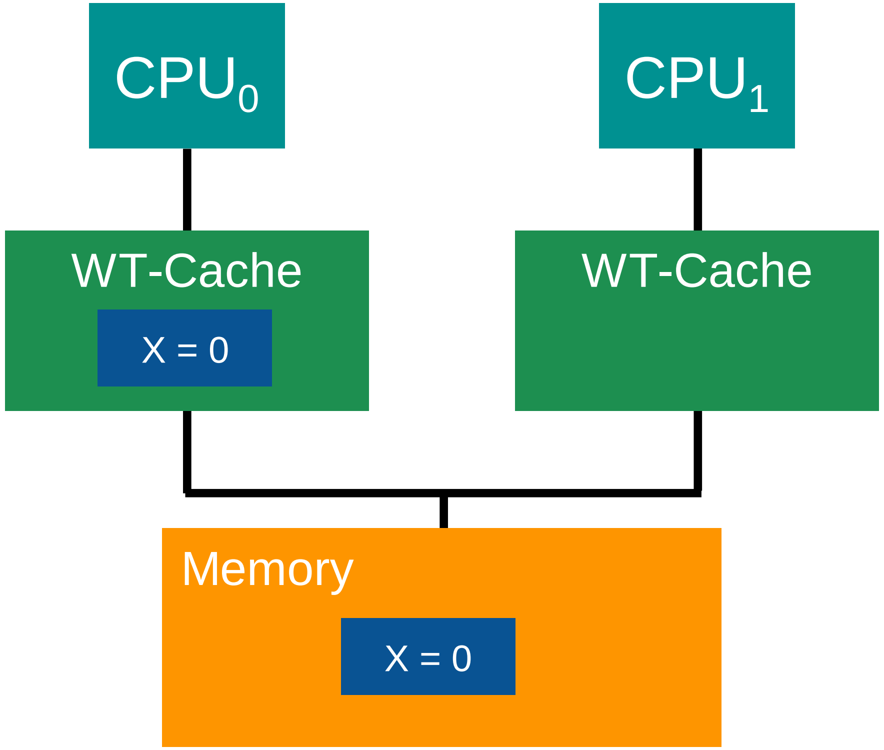
Write Through Cache



1. CPU_0 reads X from memory
   - loads X=0 into its cache

Requires write propagation!

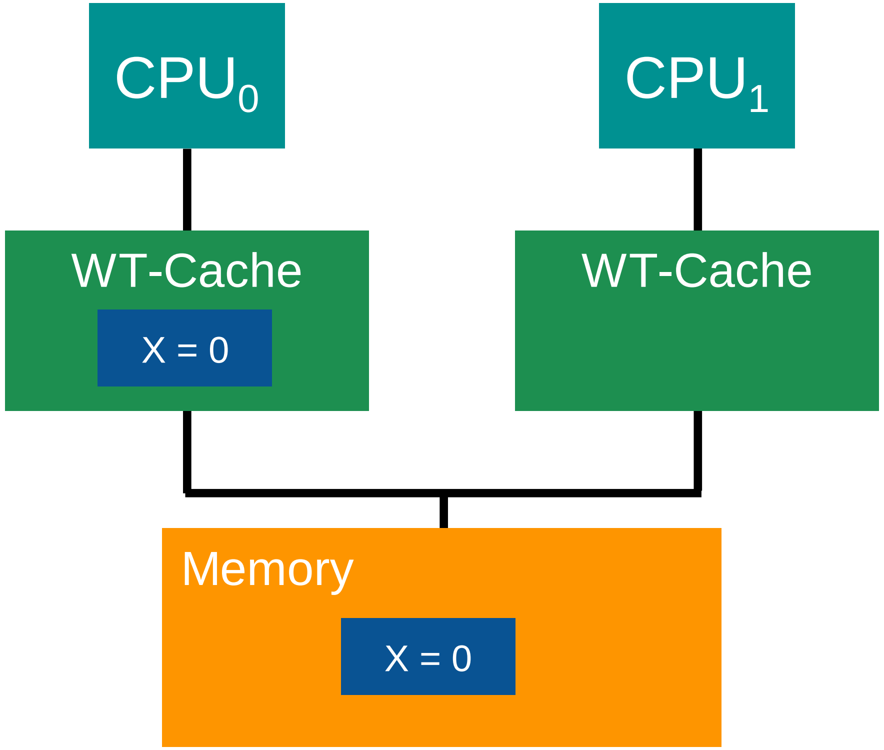
Write Through Cache



1. CPU$_0$ reads X from memory
   - loads X=0 into its cache

Requires write propagation!

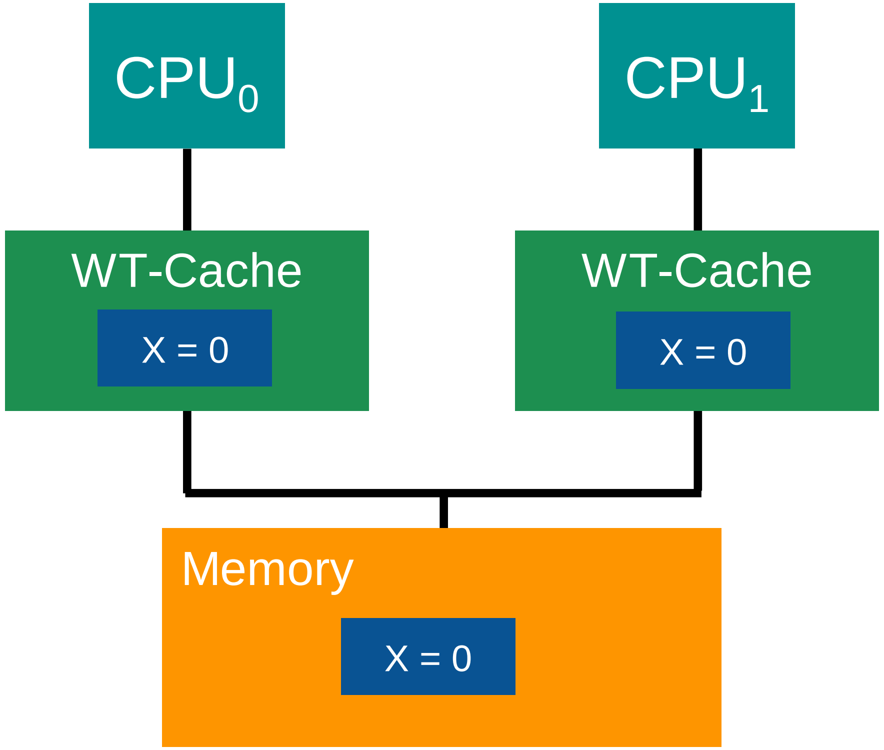
Write Through Cache



1. CPU_0 reads X from memory
   - loads X=0 into its cache
2. CPU_1 reads X from memory
   - loads X=0 into its cache

Requires write propagation!

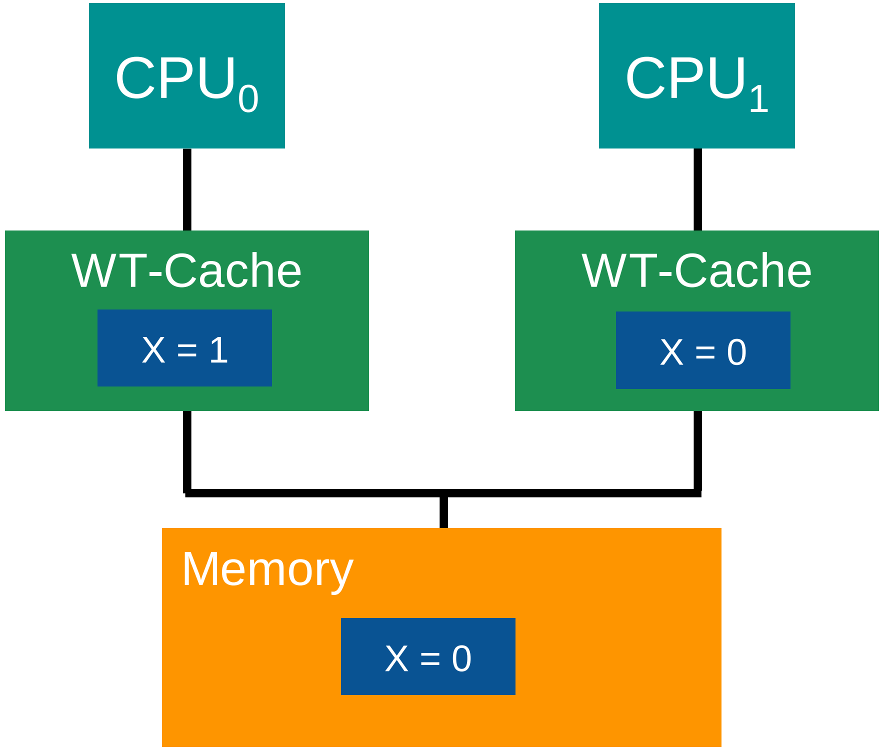
Write Through Cache



1. CPU_0 reads X from memory
   - loads X=0 into its cache
2. CPU_1 reads X from memory
   - loads X=0 into its cache

Requires write propagation!

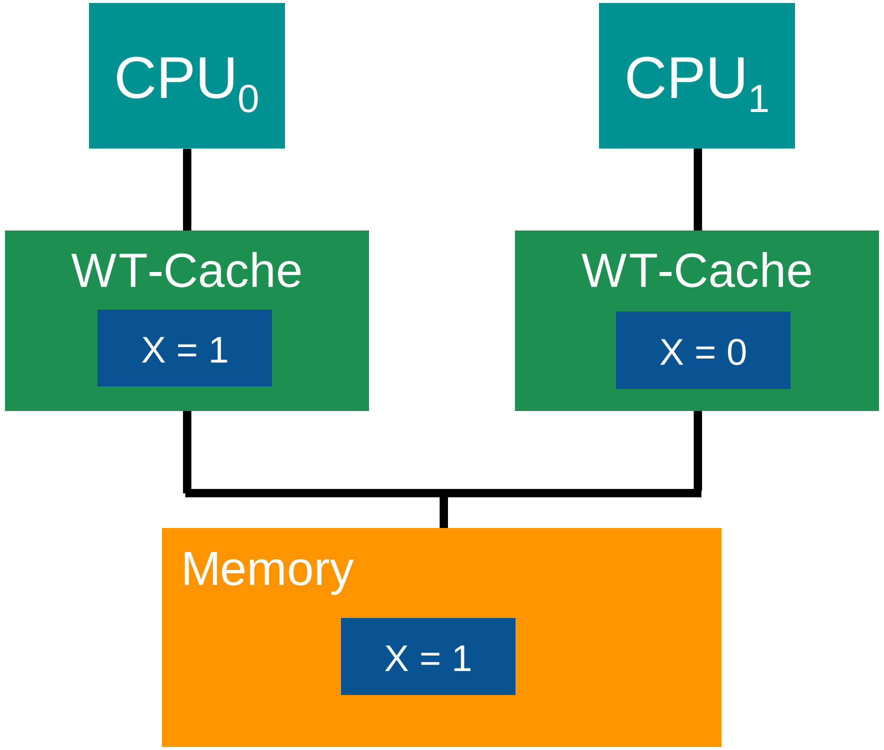
Write Through Cache



1. CPU_0 reads X from memory
   - loads X=0 into its cache
2. CPU_1 reads X from memory
   - loads X=0 into its cache
3. CPU_0 writes X=1
   - stores X=1 in its cache
   - stores X=1 in memory

Requires write propagation!

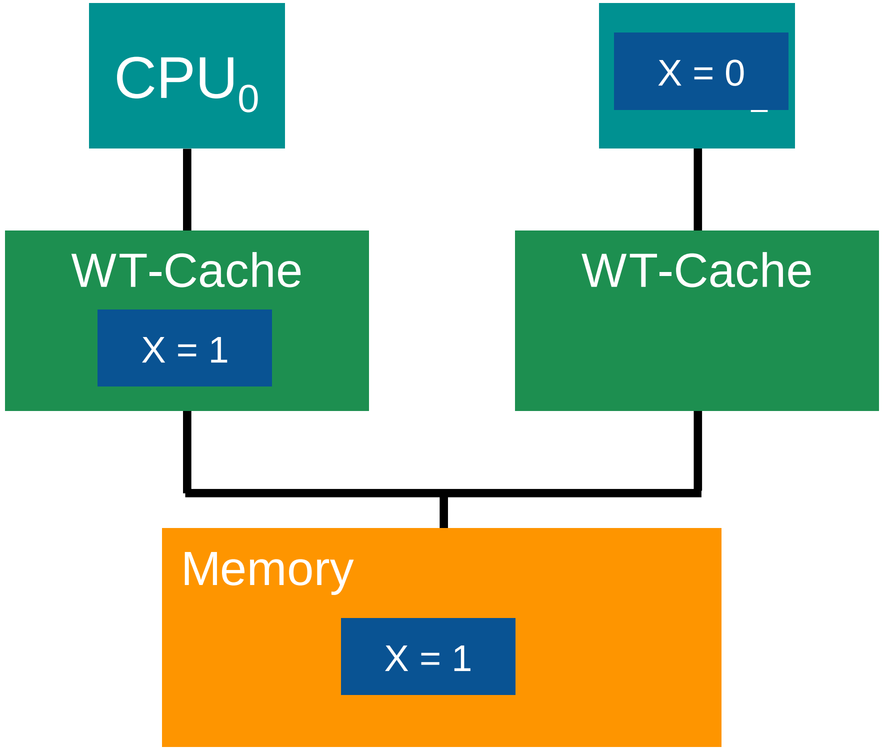
Write Through Cache



1. CPU$_0$ reads X from memory
   - loads X=0 into its cache
2. CPU$_1$ reads X from memory
   - loads X=0 into its cache
3. CPU$_0$ writes X=1
   - stores X=1 in its cache
   - stores X=1 in memory

Requires write propagation!

Write Through Cache

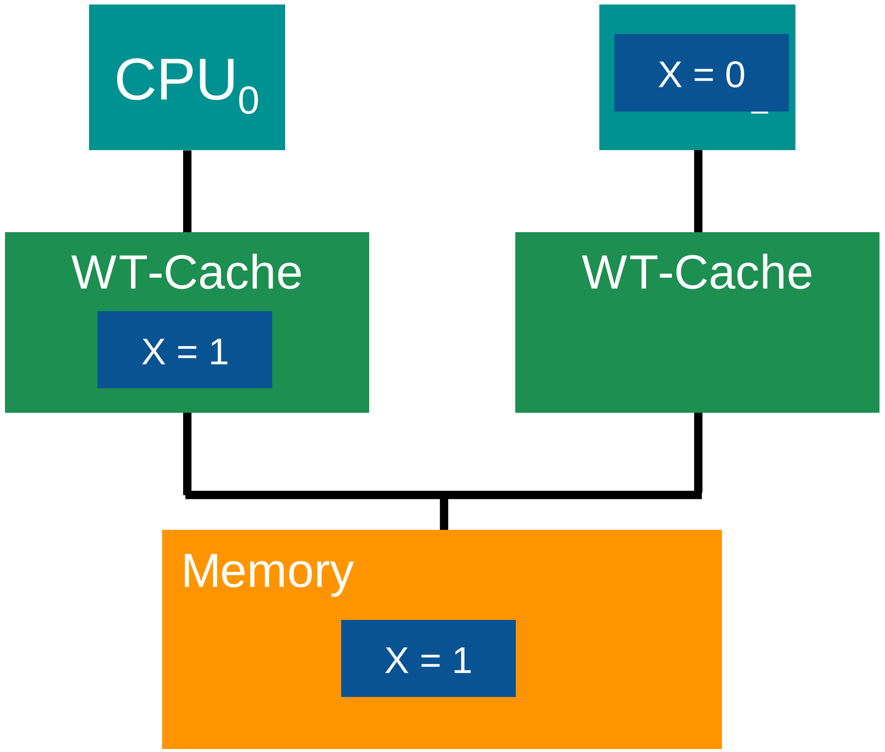


1. CPU$_0$ reads X from memory
   - loads X=0 into its cache
2. CPU$_1$ reads X from memory
   - loads X=0 into its cache
3. CPU$_0$ writes X=1
   - stores X=1 in its cache
   - stores X=1 in memory
4. CPU$_1$ reads X from its cache
   - loads X=0 from its cache

   Incoherent value for X on CPU$_1$

Requires write propagation!

Write Through Cache



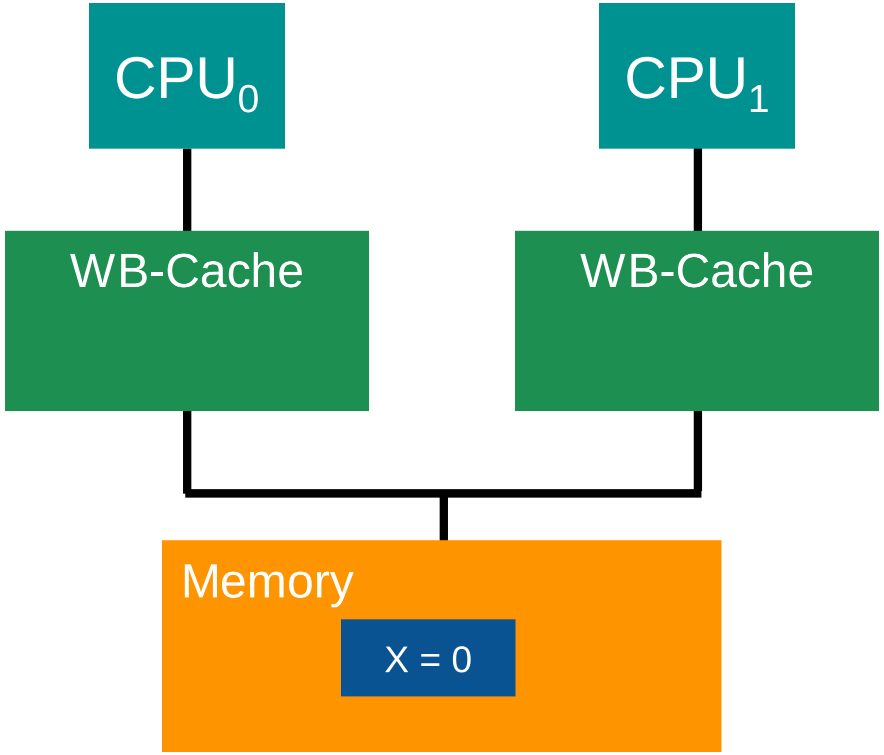
1. CPU_0 reads X from memory
   - loads X=0 into its cache
2. CPU_1 reads X from memory
   - loads X=0 into its cache
3. CPU_0 writes X=1
   - stores X=1 in its cache
   - stores X=1 in memory
4. CPU_1 reads X from its cache
   - loads X=0 from its cache

Incoherent value for X on CPU_1

CPU_1 may wait for update!

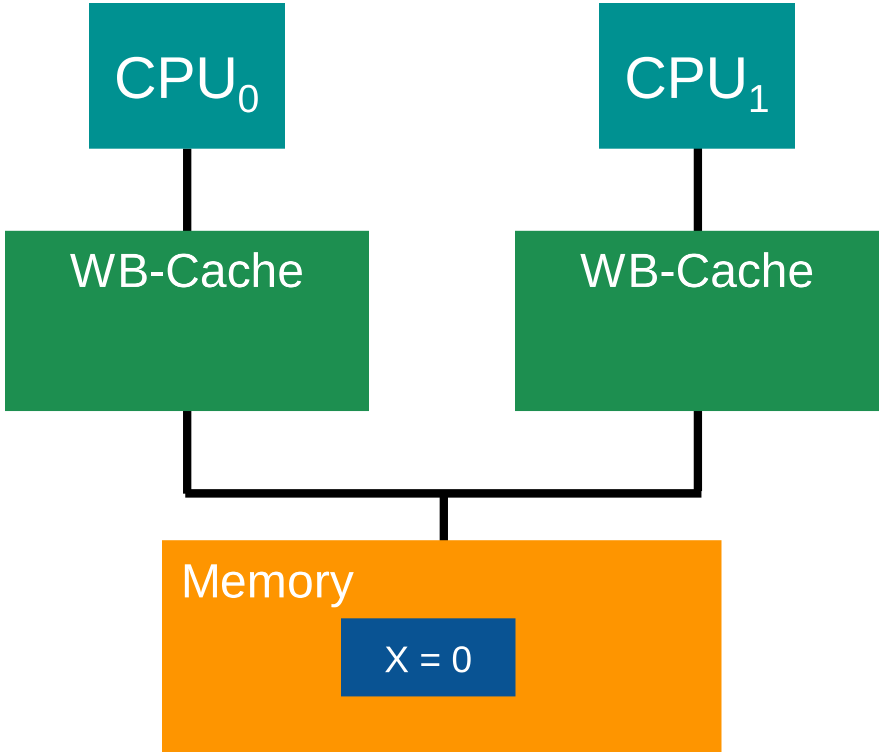
Requires write propagation!

Write Back Cache



Requires write serialization!

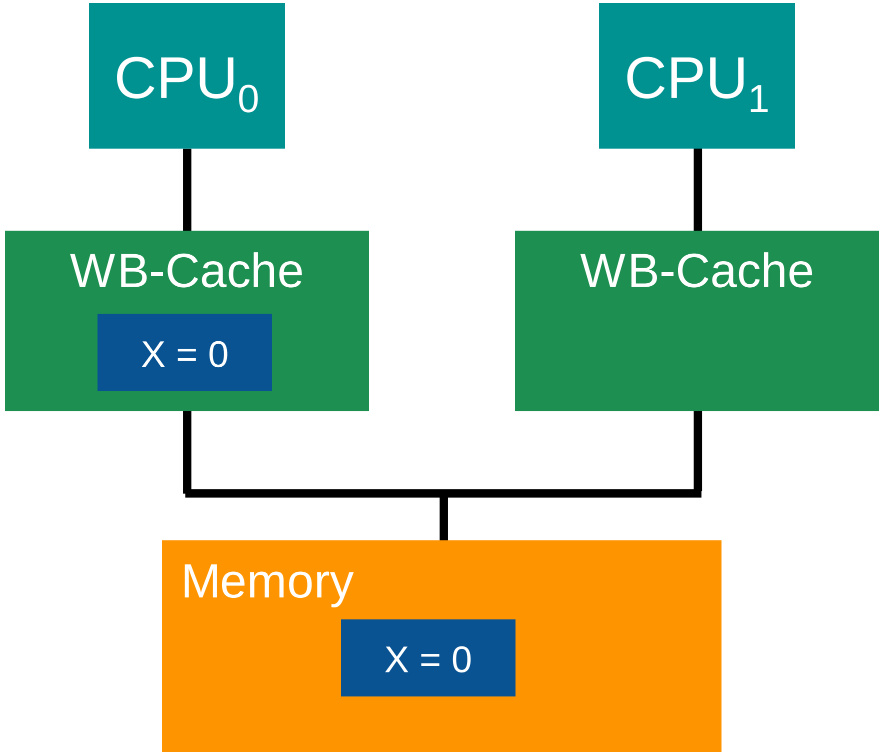
Write Back Cache



1. CPU$_0$ reads X from memory
   - loads X=0 into its cache

Requires write serialization!

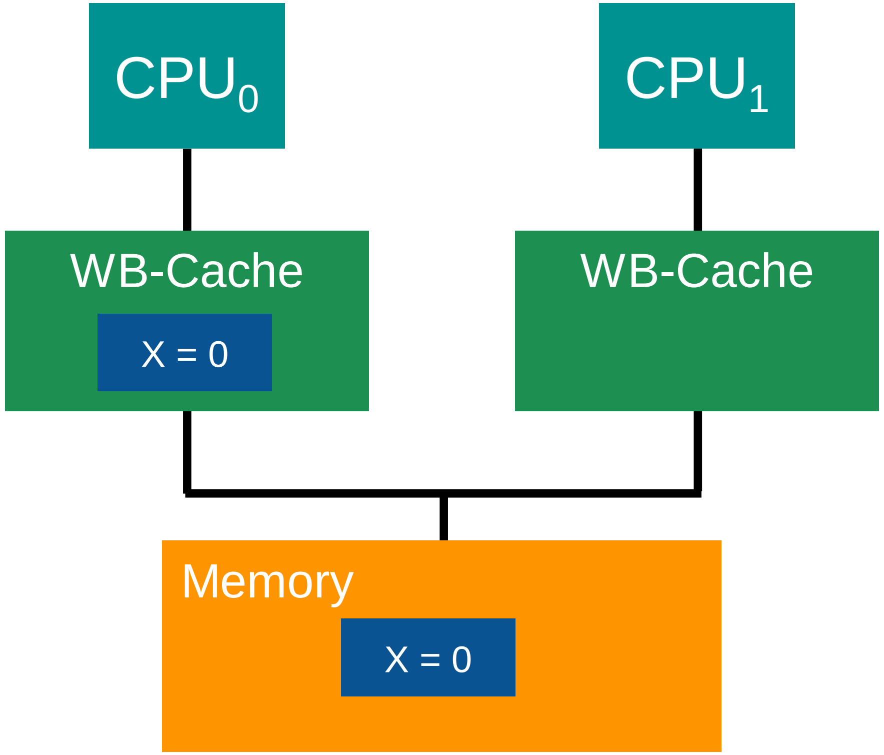
Write Back Cache



1. CPU$_0$ reads X from memory
   - loads X=0 into its cache

Requires write serialization!

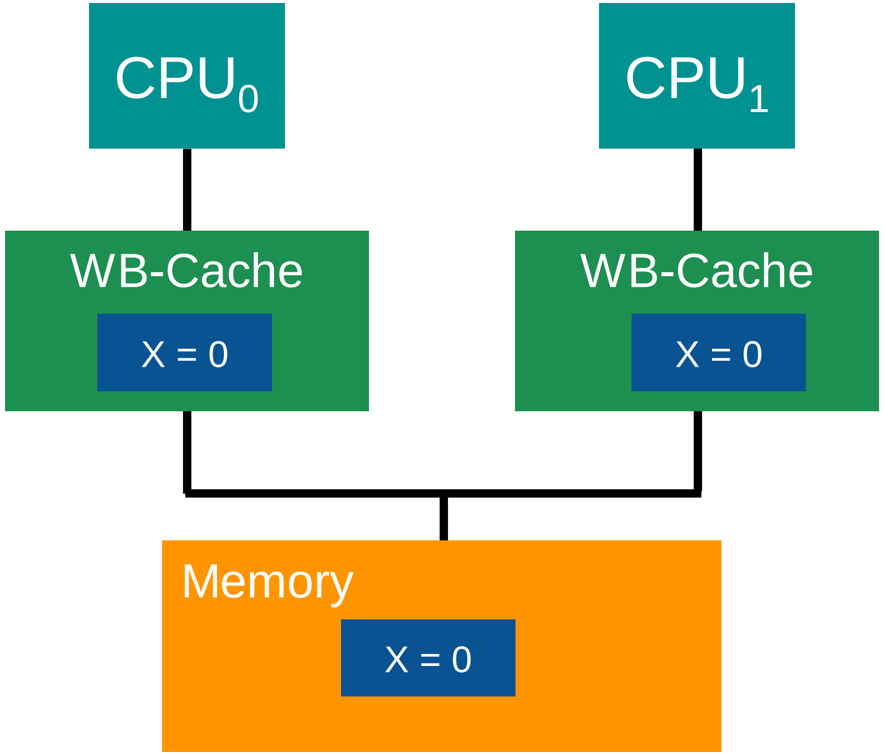
Write Back Cache



1. CPU_0 reads X from memory
   - loads X=0 into its cache
2. CPU_1 reads X from memory
   - loads X=0 into its cache

Requires write serialization!

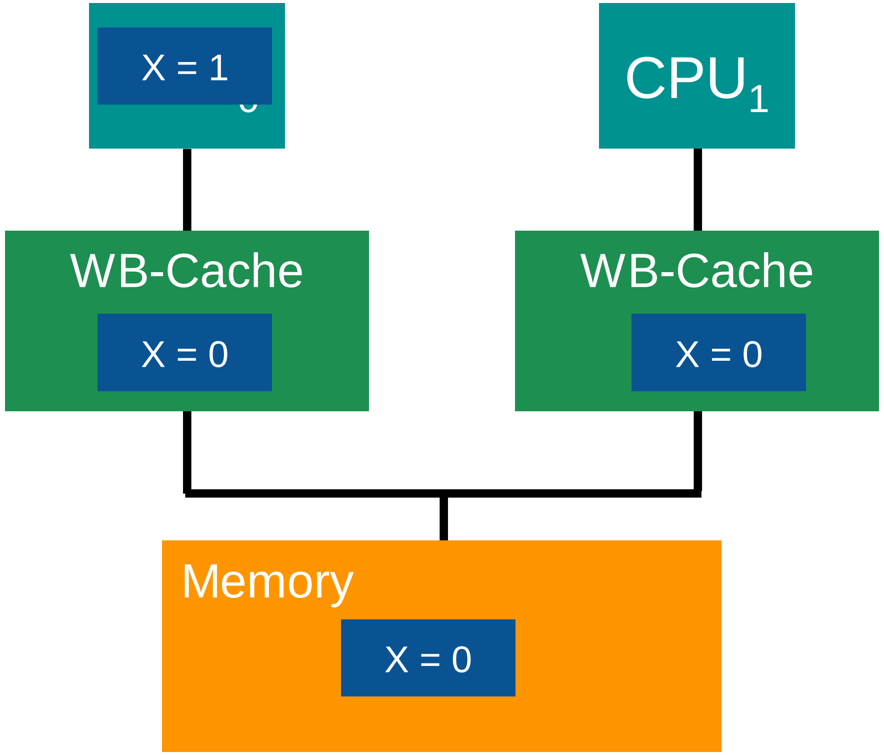
Write Back Cache



1. CPU_0 reads X from memory
   - loads X=0 into its cache
2. CPU_1 reads X from memory
   - loads X=0 into its cache

Requires write serialization!

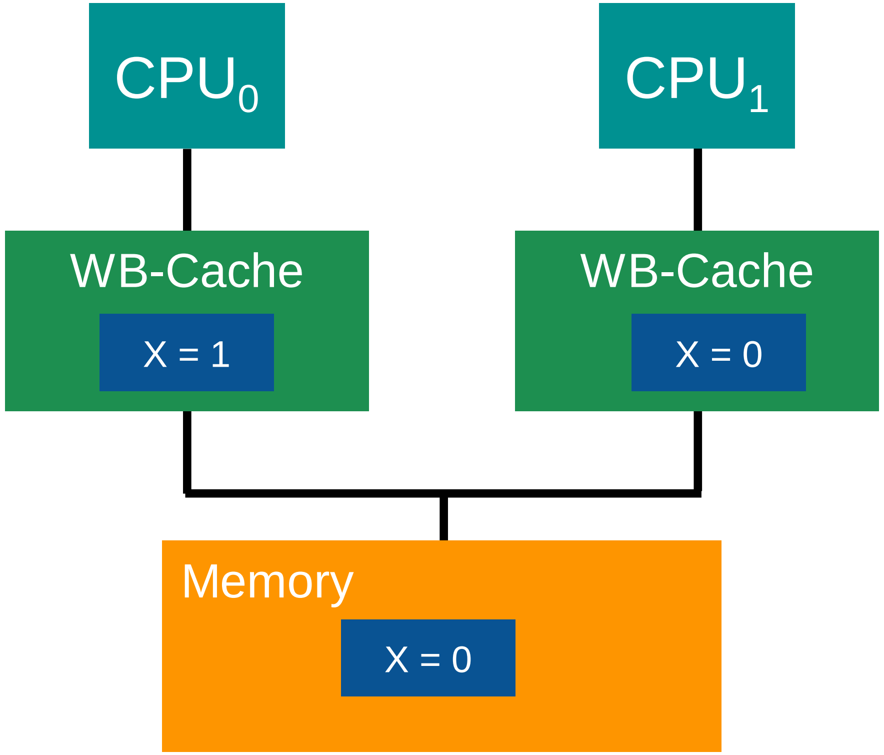
Write Back Cache



1. CPU$_0$ reads X from memory
   - loads X=0 into its cache
2. CPU$_1$ reads X from memory
   - loads X=0 into its cache
3. CPU$_0$ writes X=1
   - stores X=1 in its cache

Requires write serialization!

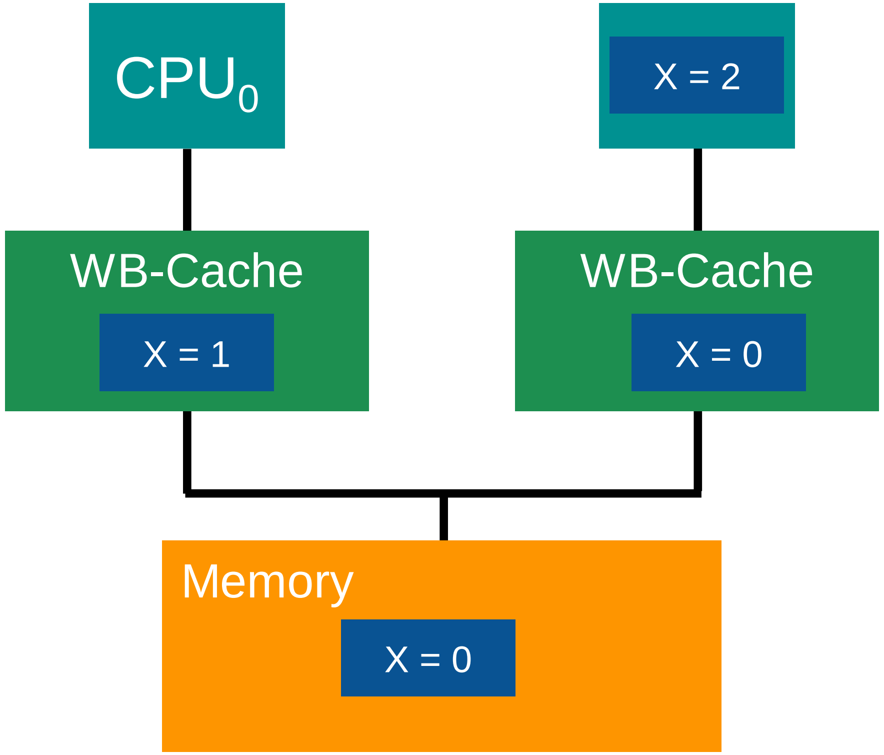
Write Back Cache



1. CPU_0 reads X from memory
   - loads X=0 into its cache
2. CPU_1 reads X from memory
   - loads X=0 into its cache
3. CPU_0 writes X=1
   - stores X=1 in its cache

Requires write serialization!

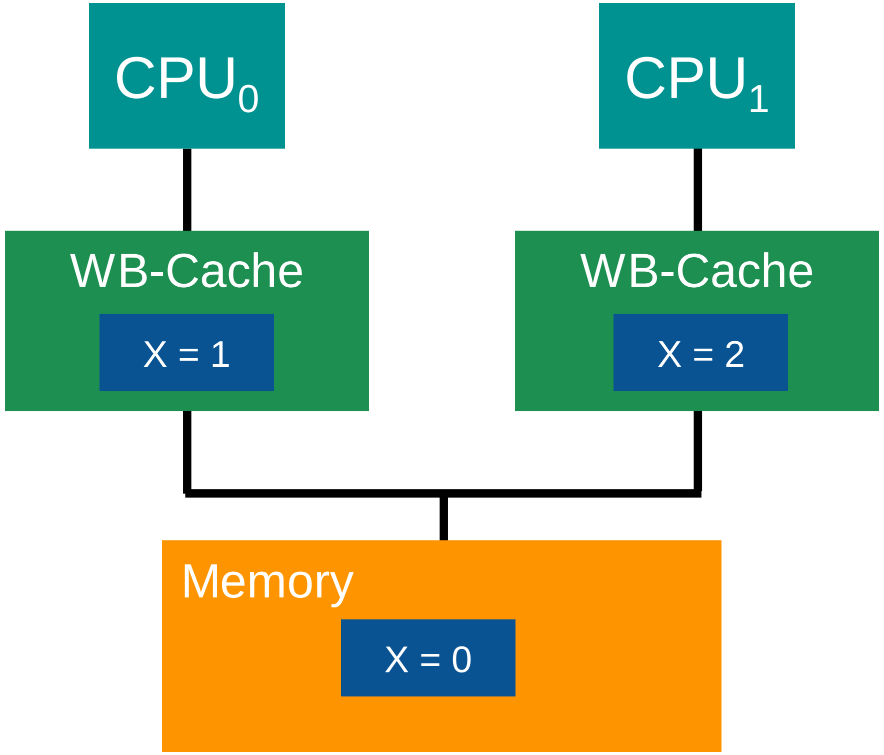
Write Back Cache



1. CPU_0 reads X from memory
   - loads X=0 into its cache
2. CPU_1 reads X from memory
   - loads X=0 into its cache
3. CPU_0 writes X=1
   - stores X=1 in its cache
4. CPU_1 writes X =2
   - stores X=2 in its cache

Requires write serialization!

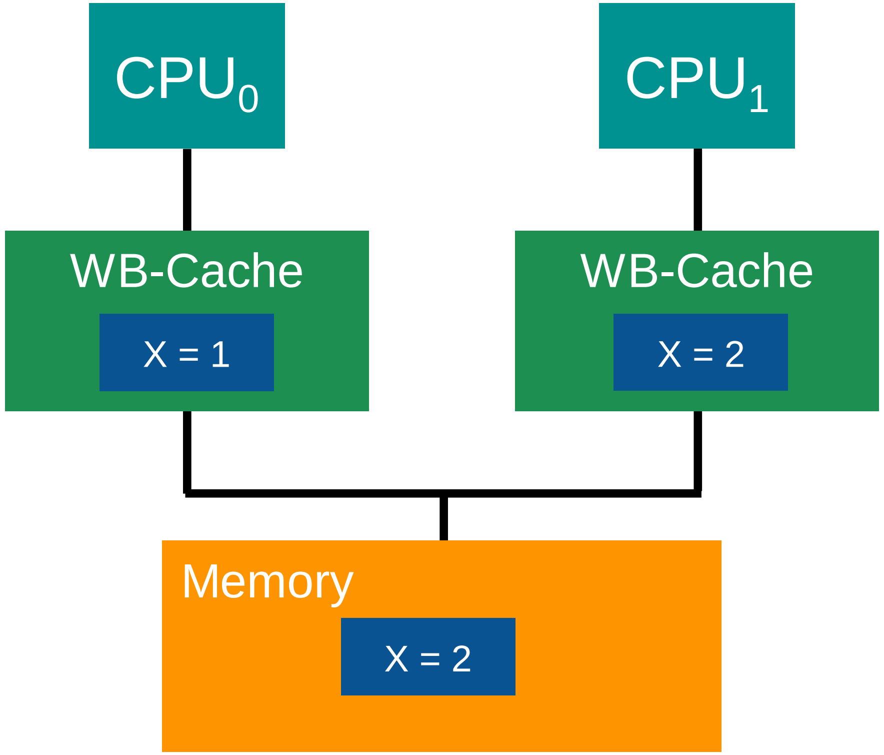
Write Back Cache



1. CPU_0 reads X from memory
   - loads X=0 into its cache
2. CPU_1 reads X from memory
   - loads X=0 into its cache
3. CPU_0 writes X=1
   - stores X=1 in its cache
4. CPU_1 writes X =2
   - stores X=2 in its cache

Requires write serialization!

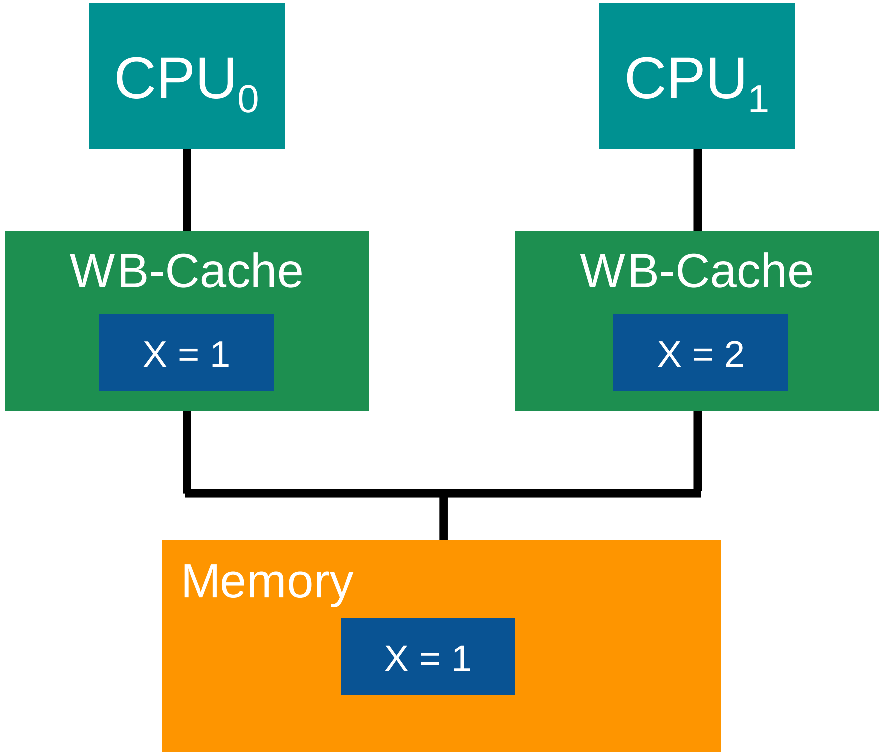
Write Back Cache



1. CPU_0 reads X from memory
   - loads X=0 into its cache
2. CPU_1 reads X from memory
   - loads X=0 into its cache
3. CPU_0 writes X=1
   - stores X=1 in its cache
4. CPU_1 writes X =2
   - stores X=2 in its cache
5. CPU_1 writes back cache line
   - stores X=2 in in memory

Requires write serialization!

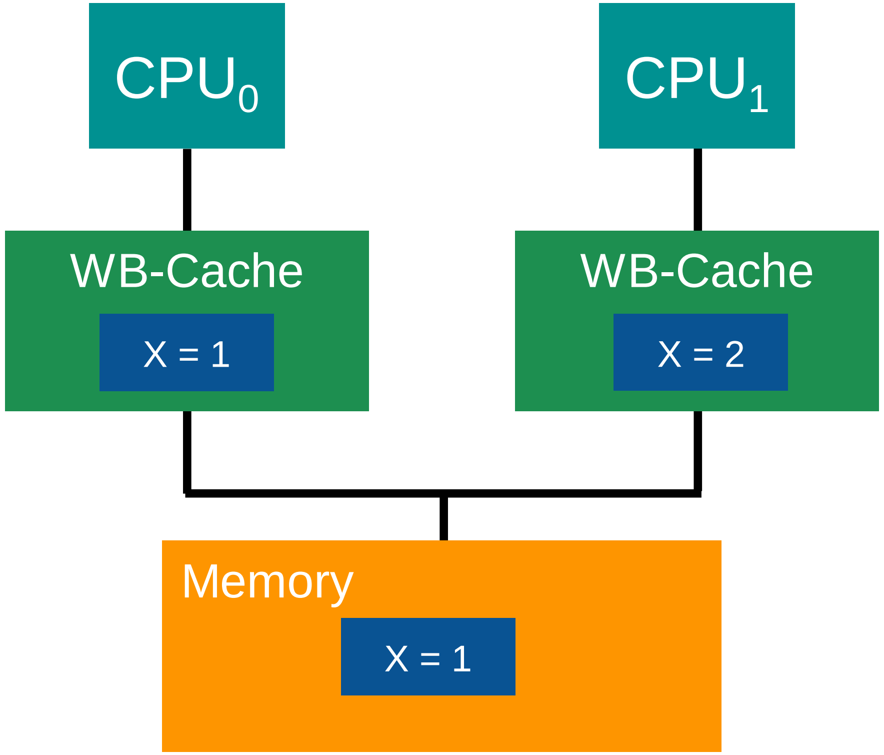
Write Back Cache



1. CPU_0 reads X from memory
   - loads X=0 into its cache
2. CPU_1 reads X from memory
   - loads X=0 into its cache
3. CPU_0 writes X=1
   - stores X=1 in its cache
4. CPU_1 writes X =2
   - stores X=2 in its cache
5. CPU_1 writes back cache line
   - stores X=2 in in memory
6. CPU_0 writes back cache line
   - stores X=1 in memory

Requires write serialization!

Write Back Cache



1. CPU_0 reads X from memory
   - loads X=0 into its cache
2. CPU_1 reads X from memory
   - loads X=0 into its cache
3. CPU_0 writes X=1
   - stores X=1 in its cache
4. CPU_1 writes X =2
   - stores X=2 in its cache
5. CPU_1 writes back cache line
   - stores X=2 in in memory
6. CPU_0 writes back cache line
   - stores X=1 in memory

Later (!) store X=2 from CPU_1 lost

Requires write serialization!

A simple (?) example

- **Assume C99:**

```c
struct twoint {
  int a;
  int b;
};
```

- **Two threads:**
  - Initially: a=b=0
  - Thread 0: write 1 to a
  - Thread 1: write 1 to b

- **Assume non-coherent write back cache**
  - What may end up in main memory?

Cache Coherence Protocol

- **Programmer can hardly deal with unpredictable behavior!**
- **Cache controller maintains data integrity**
  - All writes to different locations are visible

Fundamental Mechanisms

- **Snooping**
  - Shared bus or (broadcast) network
- **Directory-based**
  - Record information necessary to maintain coherence:
    E.g., owner and state of a line etc.

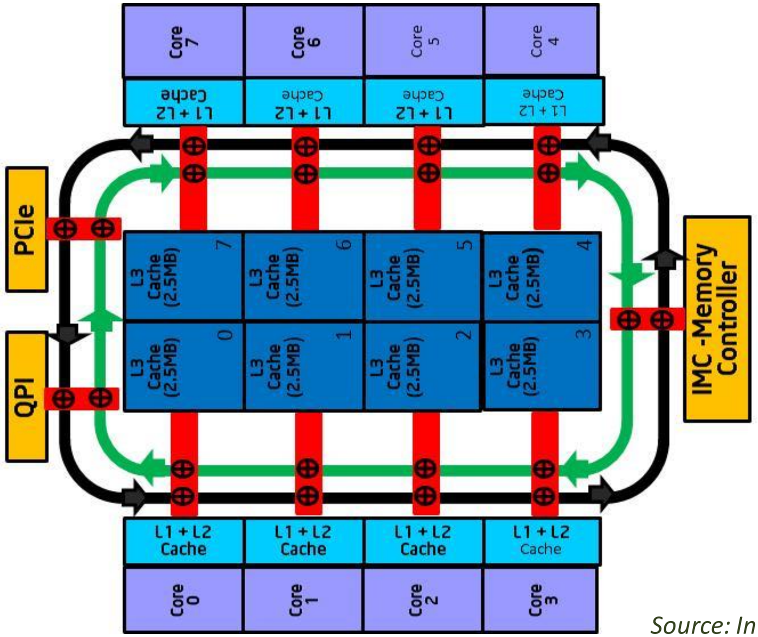
Fundamental CC mechanisms

- **Snooping**
  - Shared bus or (broadcast) network
  - Cache controller “snoops” all transactions
  - Monitors and changes the state of the cache’s data
  - Works at small scale, challenging at large-scale

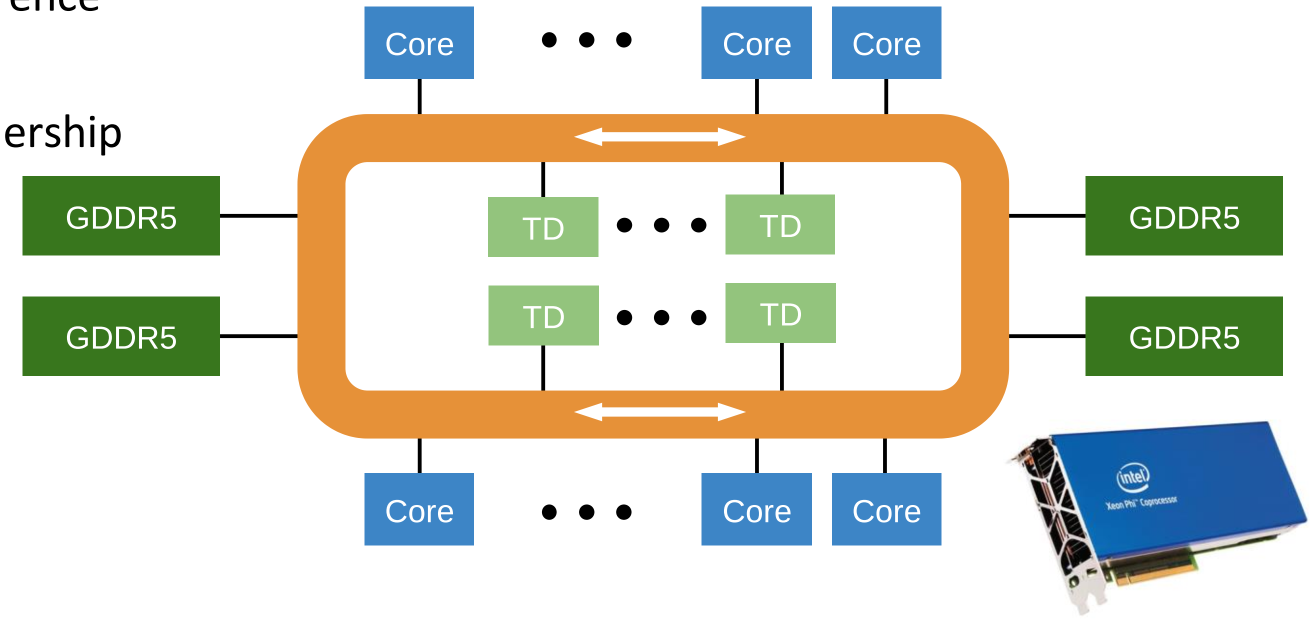
    E.g., Intel Core (Broadwell, …)
- **Directory-based**
  - Record information necessary to maintain coherence

    E.g., owner and state of a line etc.
  - Central/Distributed directory for cache line ownership
  - Scalable but more complex/expensive

    E.g., Intel Xeon Phi KNC/KNL



Source: Intel



Cache Coherence Parameters

- **Concerns/Goals**
  - Performance
  - Implementation cost (chip space, more important: dynamic energy)
  - Correctness
  - (Memory model side effects)

- **Issues**
  - Detection (when does a controller need to act)
  - Enforcement (how does a controller guarantee coherence)
  - Precision of block sharing (per block, per sub-block?)
  - Block size (cache line size?)

An Engineering Approach: Empirical start

- **Problem 1: stale reads**
  - Cache 1 holds value that was already modified in cache 2
  - Solution:

    Disallow this state

    Invalidate all remote copies before allowing a write to complete

- **Problem 2: lost update**
  - Incorrect write back of modified line writes main memory in different order from the order of the write operations or overwrites neighboring data
  - Solution:

    Disallow more than one modified copy

Invalidation vs. update – possible implementations

- **Invalidation-based:**
  - On each write of a shared line, it has to invalidate copies in remote caches
  - Simple implementation for bus-based systems:

    Each cache snoops

    Invalidate lines written by other CPUs

    Signal sharing for cache lines in local cache to other caches
- **Update-based:**
  - Local write updates copies in remote caches

    Can update all CPUs at once

    Multiple writes cause multiple updates (more traffic)

Invalidation vs. update – effects

- **Invalidation-based:**
  - Only write misses hit the bus (works with write-back caches)
  - Subsequent writes to the same cache line are local
  - → Good for multiple writes to the same line (in the same cache)

- **Update-based:**
  - All sharers continue to hit cache line after one core writes

    Implicit assumption: shared lines are accessed often
  - Supports producer-consumer pattern well
  - Many (local) writes may waste bandwidth!

- **Hybrid forms are possible!**

MESI Cache Coherence

- **Most common hardware implementation of discussed requirements**

  aka. “Illinois protocol”

Each line has one of the following states (in a cache):

- **Modified (M)**
  - Local copy has been modified, no copies in other caches
  - Memory is stale
- **Exclusive (E)**
  - No copies in other caches
  - Memory is up to date
- **Shared (S)**
  - Unmodified copies *may* exist in other caches
  - Memory is up to date
- **Invalid (I)**
  - Line is not in cache

Terminology

- **Clean line:**
  - Content of cache line and main memory is identical (also: memory is up to date)
  - Can be evicted without write-back
- **Dirty line:**
  - Content of cache line and main memory differ (also: memory is stale)
  - Needs to be written back eventually

    Time depends on protocol details
- **Bus transaction:**
  - A signal on the bus that can be observed by all caches
  - Usually blocking
- **Local read/write:**
  - A load/store operation originating at a core connected to the cache

Transitions in response to local reads

- **State is M**
  - No bus transaction
- **State is E**
  - No bus transaction
- **State is S**
  - No bus transaction
- **State is I**
  - Generate bus read request (BusRd)
    May force other cache operations (see later)
  - Other cache(s) signal “sharing” if they hold a copy
  - If shared was signaled, go to state S
  - Otherwise, go to state E
- **After update: return read value**

Transitions in response to local writes

- **State is M**
  - No bus transaction
- **State is E**
  - No bus transaction
  - Go to state M
- **State is S**
  - Line already local & clean
  - There may be other copies
  - Generate bus read request for upgrade to exclusive (BusRdX*)
  - Go to state M
- **State is I**
  - Generate bus read request for exclusive ownership (BusRdX)
  - Go to state M

Transitions in response to snooped BusRd

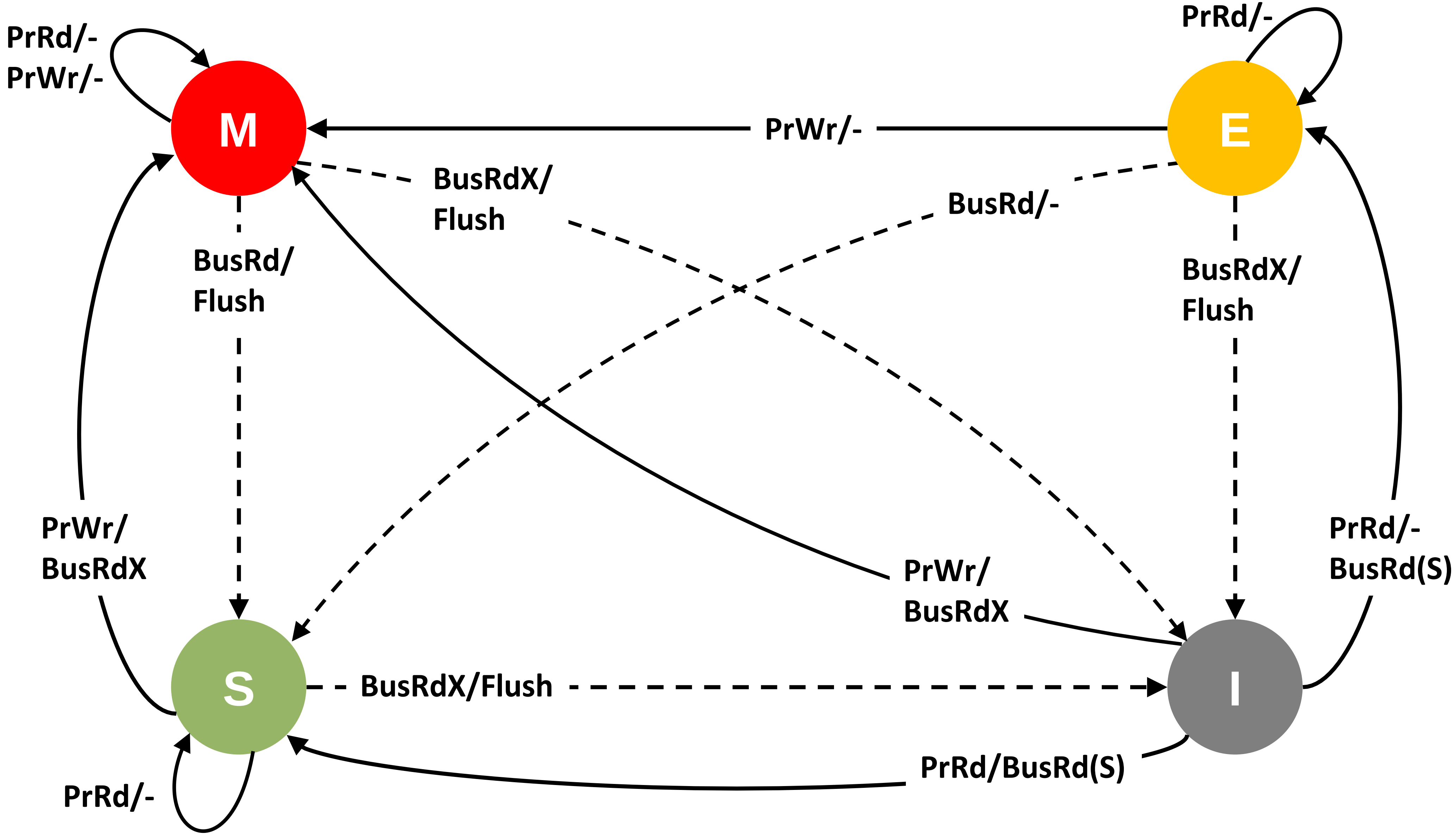
- **State is M**
  - Write cache line back to main memory
  - Signal “shared”
  - Go to state S (or E)
- **State is E**
  - Signal “shared”
  - Go to state S and signal “shared”
- **State is S**
  - Signal “shared”
- **State is I**
  - Ignore

Transitions in response to snooped BusRdX

- **State is M**
  - Write cache line back to memory
  - Discard line and go to I
- **State is E**
  - Discard line and go to I
- **State is S**
  - Discard line and go to I
- **State is I**
  - Ignore

- **BusRdX* is handled like BusRdX!**

MESI State Diagram (FSM)



Small Exercise

- **Initially: all in I state**

Action	P1 state	P2 state	P3 state	Bus action	Data from
P1 reads x					
P2 reads x					
P1 writes x					
P1 reads x					
P3 writes x					

Small Exercise

- **Initially: all in I state**

Action	P1 state	P2 state	P3 state	Bus action	Data from
P1 reads x	E	I	I	BusRd	Memory
P2 reads x	S	S	I	BusRd	Cache
P1 writes x	M	I	I	BusRdX*	Cache
P1 reads x	M	I	I	-	Cache
P3 writes x	I	I	M	BusRdX	Memory

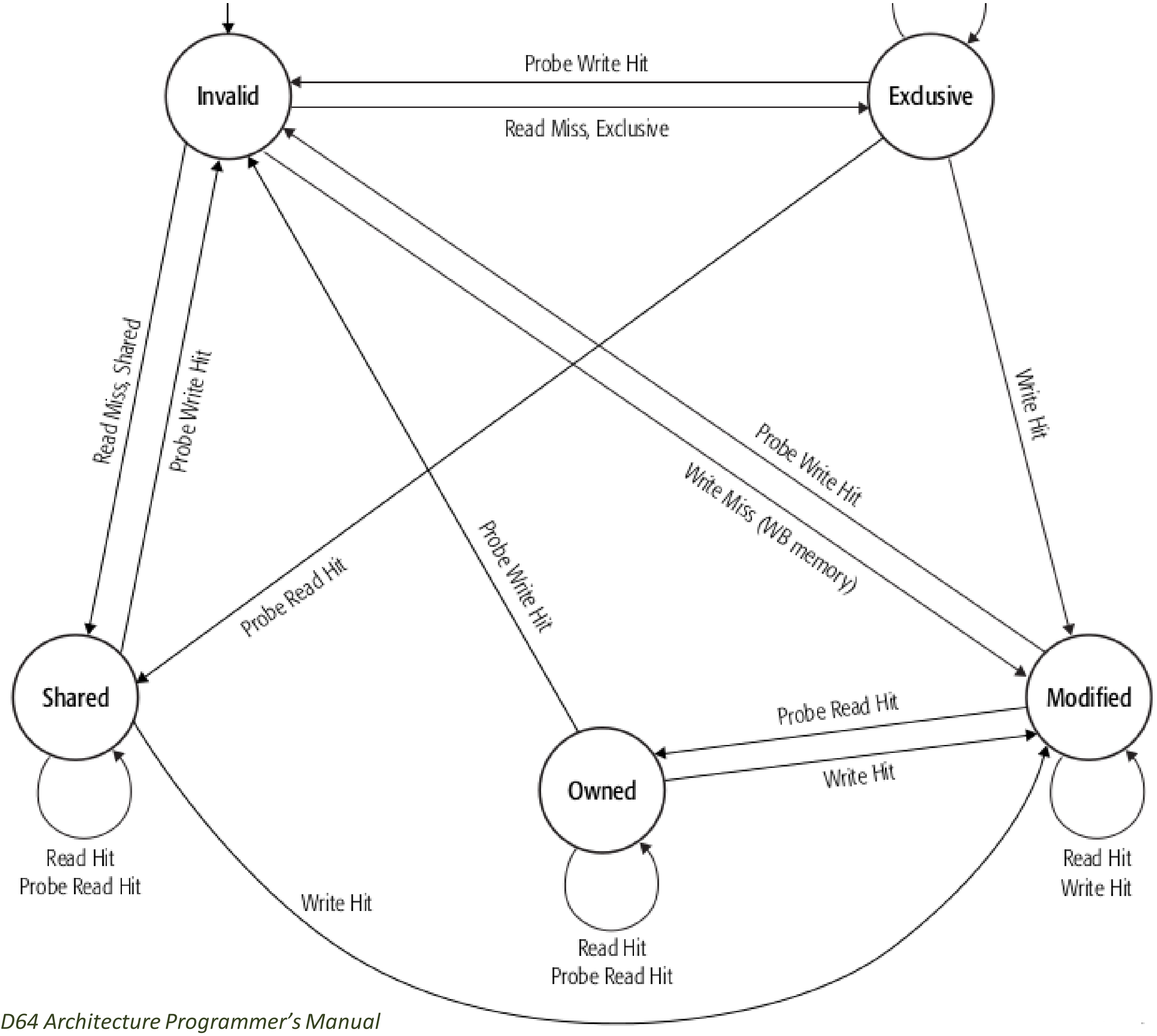
Optimizations?

- **Class question: what could be optimized in the MESI protocol to make a system faster?**

Related Protocols: MOESI (AMD)

- **Extended MESI protocol**
- **Cache-to-cache transfer of modified cache lines**
  - Cache in M or O state always transfers cache line to requesting cache
  - No need to contact (slow) main memory
- **Avoids write back when another process accesses cache line**
  - Good when cache-to-cache performance is higher than cache-to-memory
    E.g., shared last level cache!

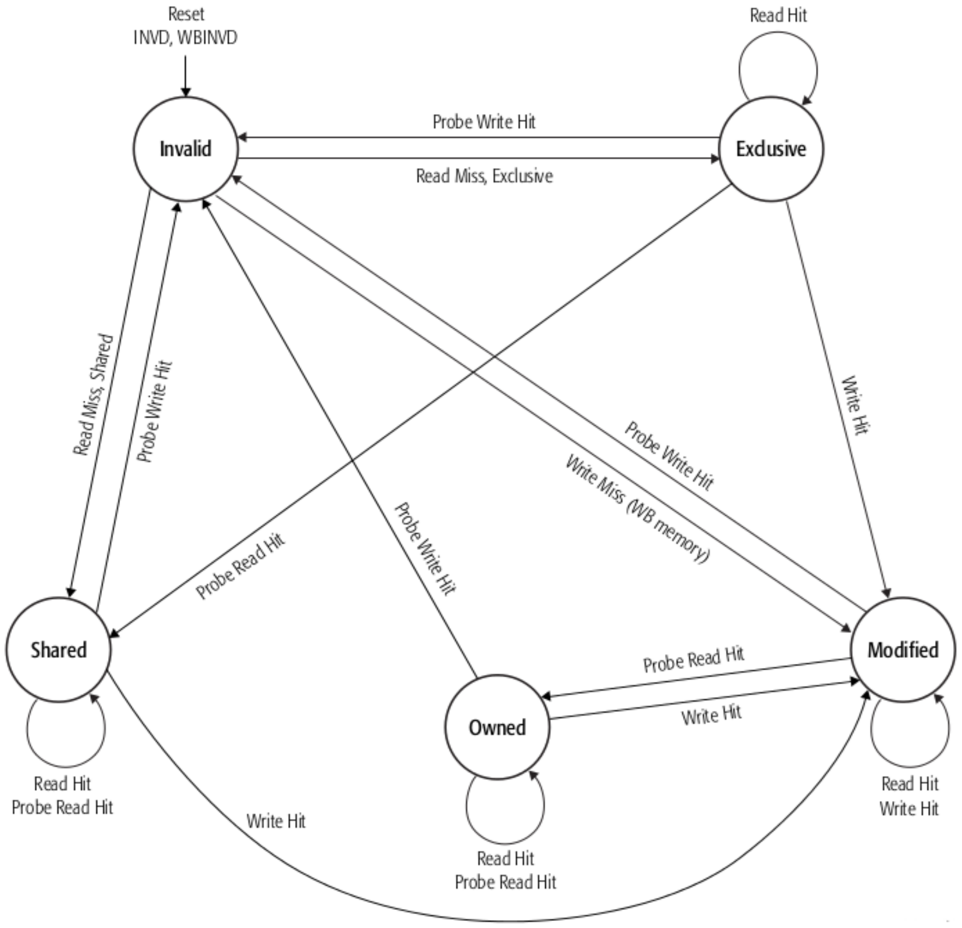
MOESI State Diagram



Source: AMD64 Architecture Programmer's Manual

Related Protocols: MOESI (AMD)

- **Modified (M): Modified Exclusive**
  - No copies in other caches, local copy dirty
  - Memory is stale, cache supplies copy (reply to BusRd*)
- **Owner (O): Modified Shared**
  - Exclusive right to make changes
  - Other S copies may exist (“dirty sharing”)
  - Memory is stale, cache supplies copy (reply to BusRd*)
- **Exclusive (E):**
  - Same as MESI (one local copy, up to date memory)
- **Shared (S):**
  - Unmodified copy may exist in other caches
  - Memory is up to date unless an O copy exists in another cache
- **Invalid (I):**
  - Same as MESI



Related Protocols: MESIF (Intel)

- **Modified (M): Modified Exclusive**
  - No copies in other caches, local copy dirty
  - Memory is stale, cache supplies copy (reply to BusRd*)
- **Exclusive (E):**
  - Same as MESI (one local copy, up to date memory)
- **Shared (S):**
  - Unmodified copy may exist in other caches
  - Memory is up to date
- **Invalid (I):**
  - Same as MESI
- **Forward (F):**
  - Special form of S state, other caches may have line in S
  - Most recent requester of line is in F state
  - Cache acts as responder for requests to this line

Multi-level caches

- **Most systems have multi-level caches**
  - Problem: only “last level cache” is connected to bus or network
  - Yet, snoop requests are relevant for inner-levels of cache (L1)
  - Modifications of L1 data may not be visible at L2 (and thus the bus)
- **L1/L2 modifications**
  - On BusRd check if line is in M state in L1

    It may be in E or S in L2!
  - On BusRdX(*) send invalidations to L1
  - Everything else can be handled in L2
- **If L1 is write through, L2 could “remember” state of L1 cache line**
  - May increase traffic though

Directory-based cache coherence

- **Snooping does not scale**
  - Bus transactions must be *globally* visible
  - Implies broadcast
- **Typical solution: tree-based (hierarchical) snooping**
  - Root becomes a bottleneck
- **Directory-based schemes are more scalable**
  - Directory (entry for each CL) keeps track of all owning caches
  - Point-to-point update to involved processors

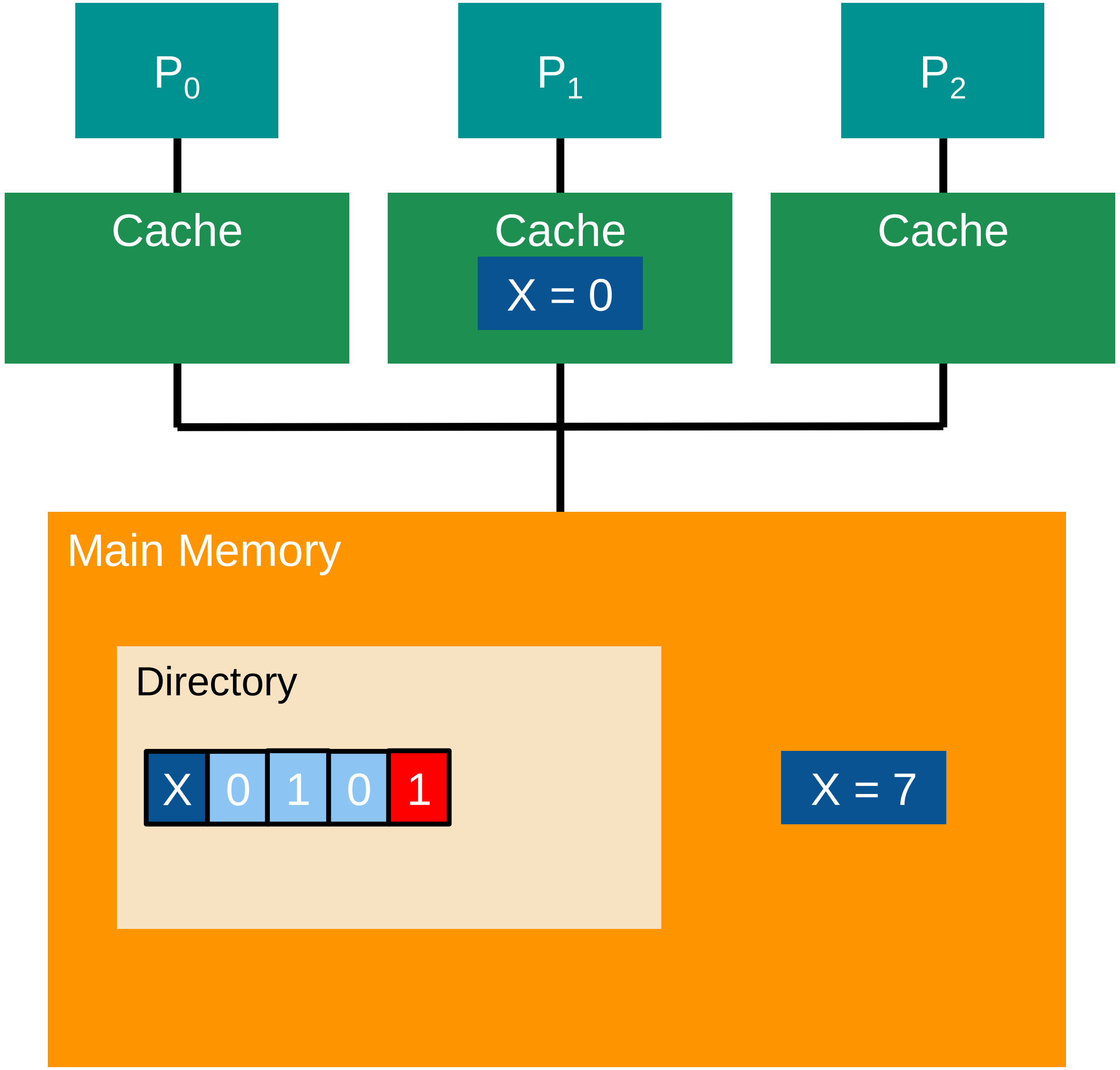
    No broadcast

    Can use specialized (high-bandwidth) network, e.g., HT, QPI …

Basic Scheme

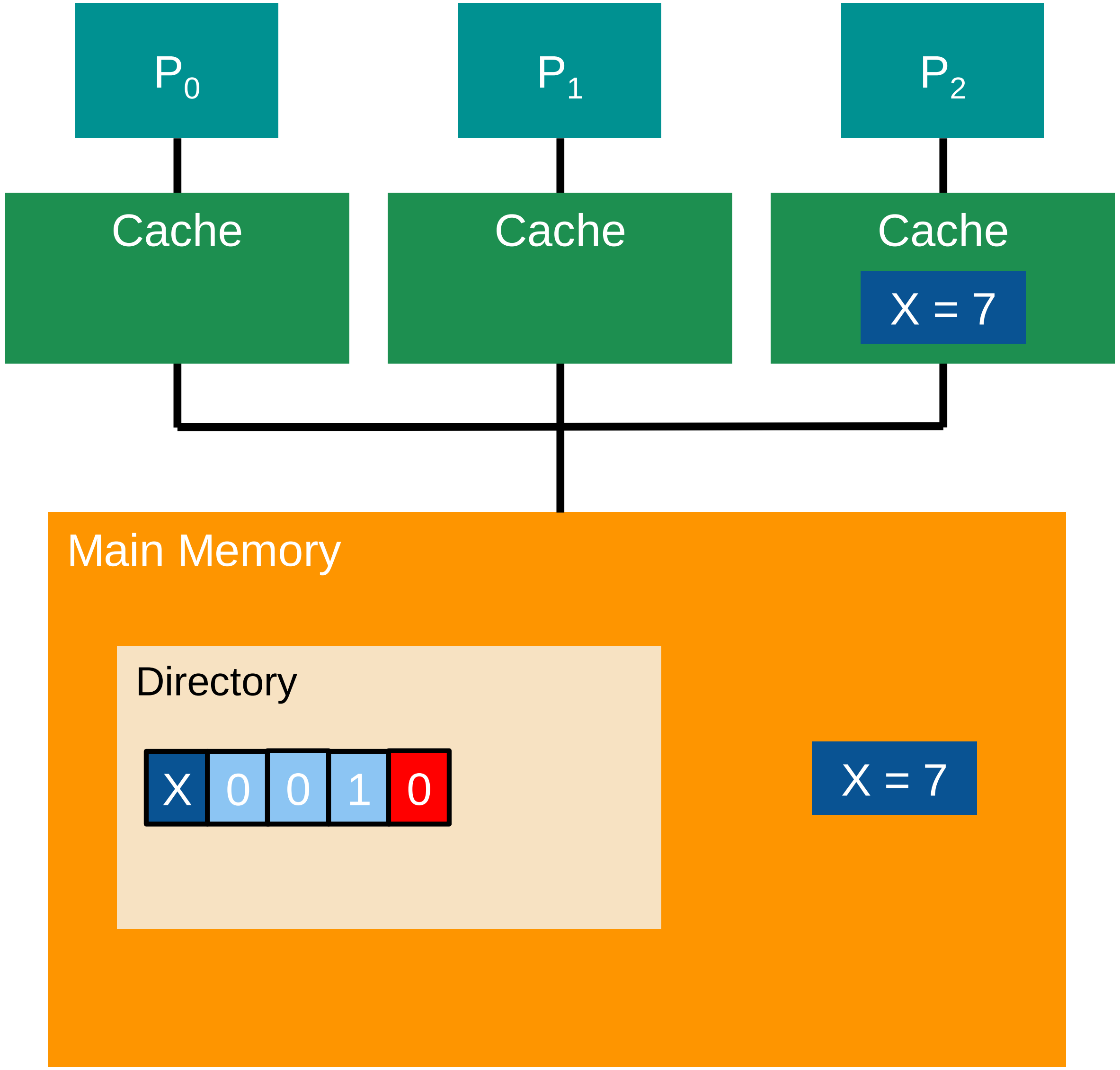
- System with N processors P_i
- For each memory block (size: cache line) maintain a directory entry
  - N presence bits (light blue)

    Set if block in cache of P_i
  - 1 dirty bit (red)
- First proposed by Censier and Feautrier (1978)



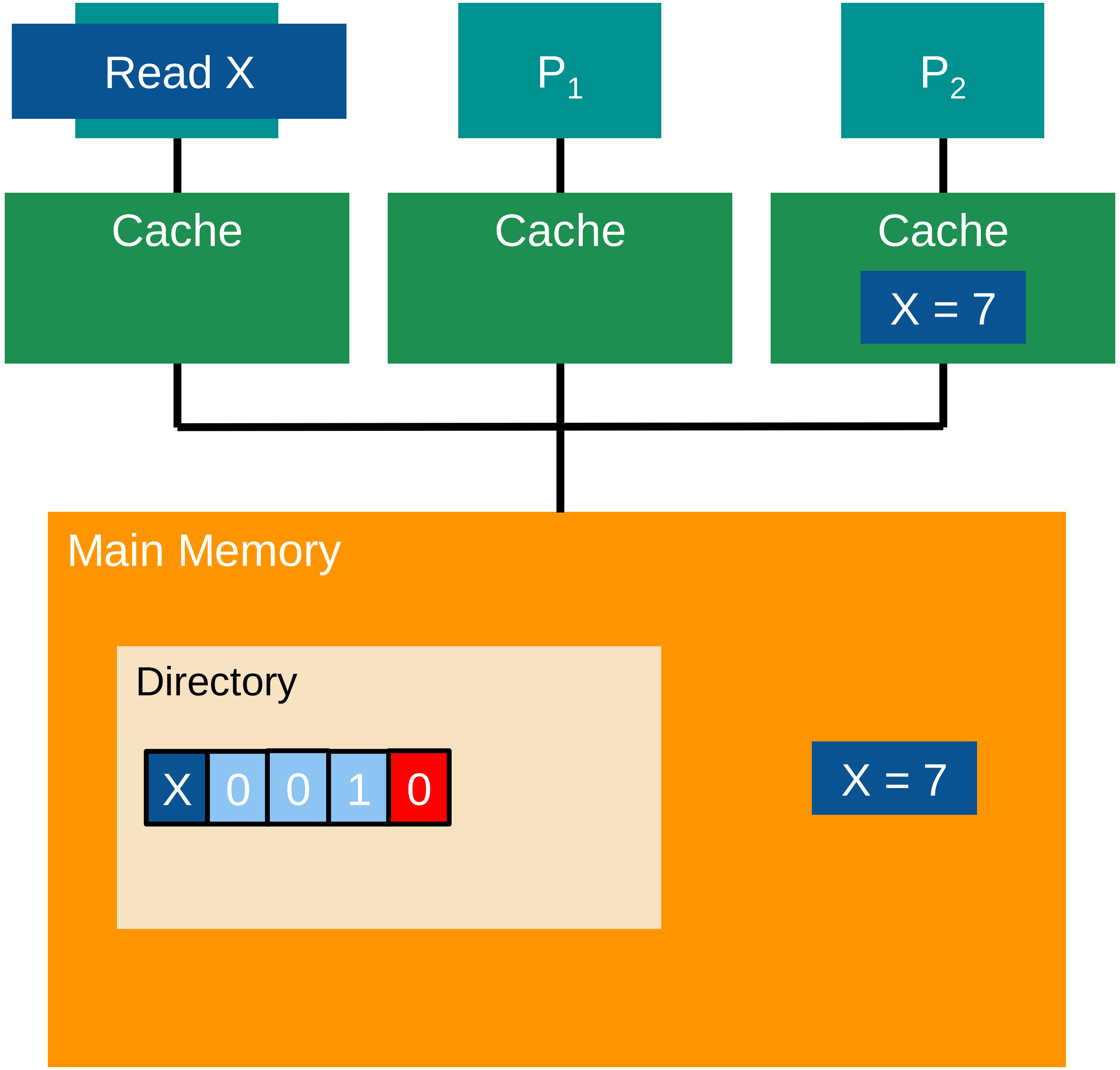
Directory-based CC: Read miss

- P_0 intends to read, misses



Directory-based CC: Read miss

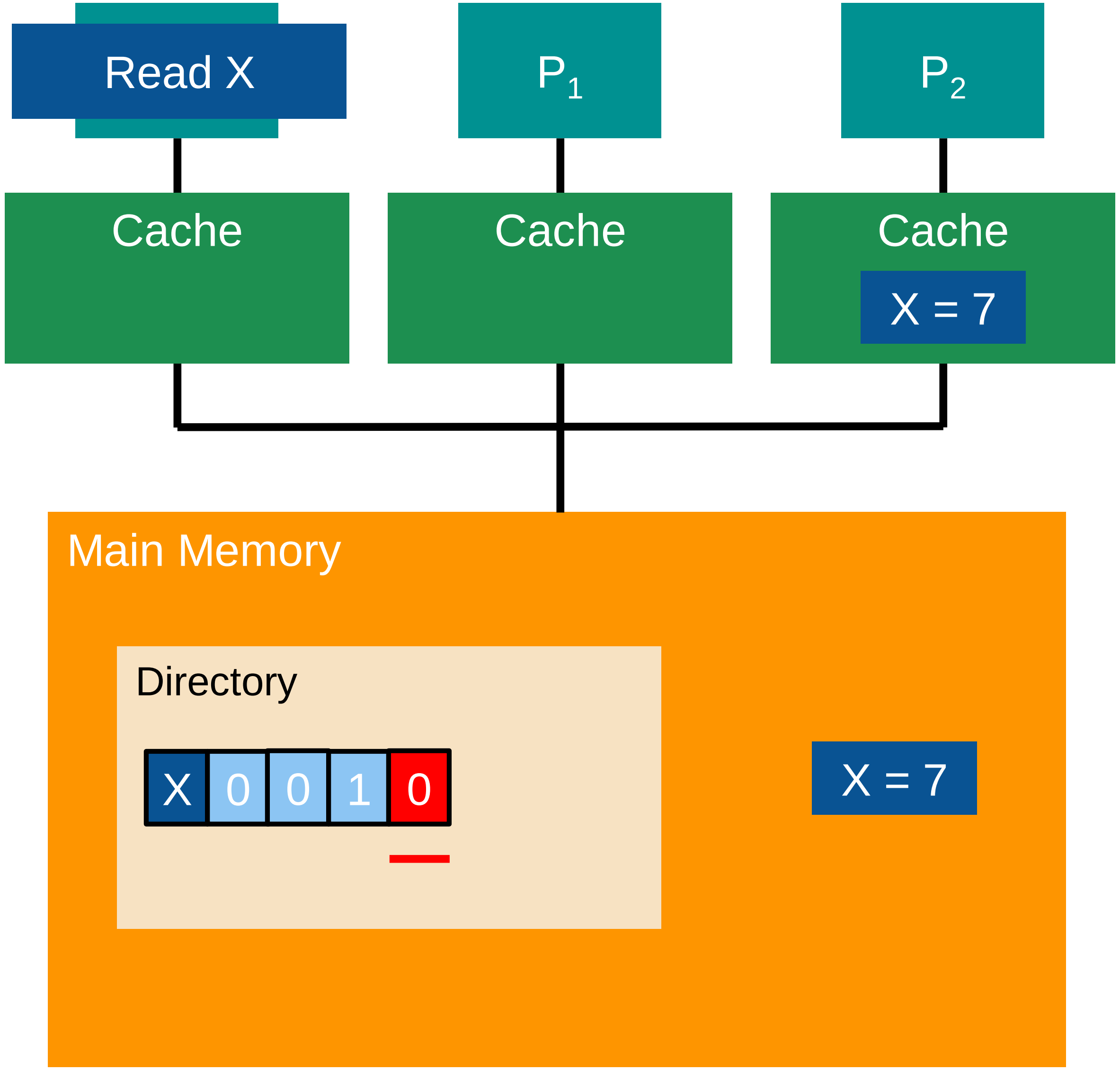
- P_0 intends to read, misses



Directory-based CC: Read miss

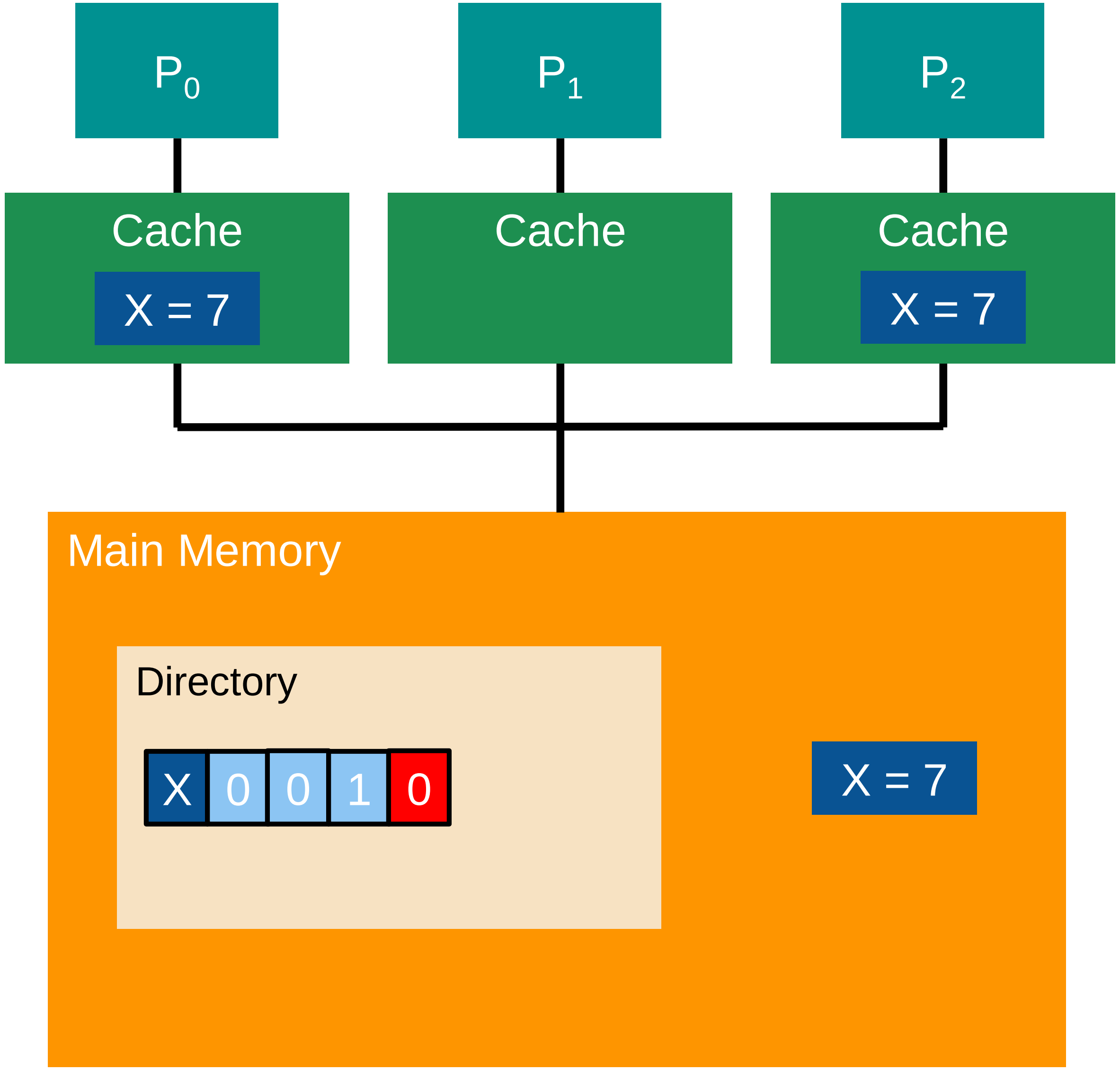
- P_0 intends to read, misses

- If dirty bit (in directory) is off



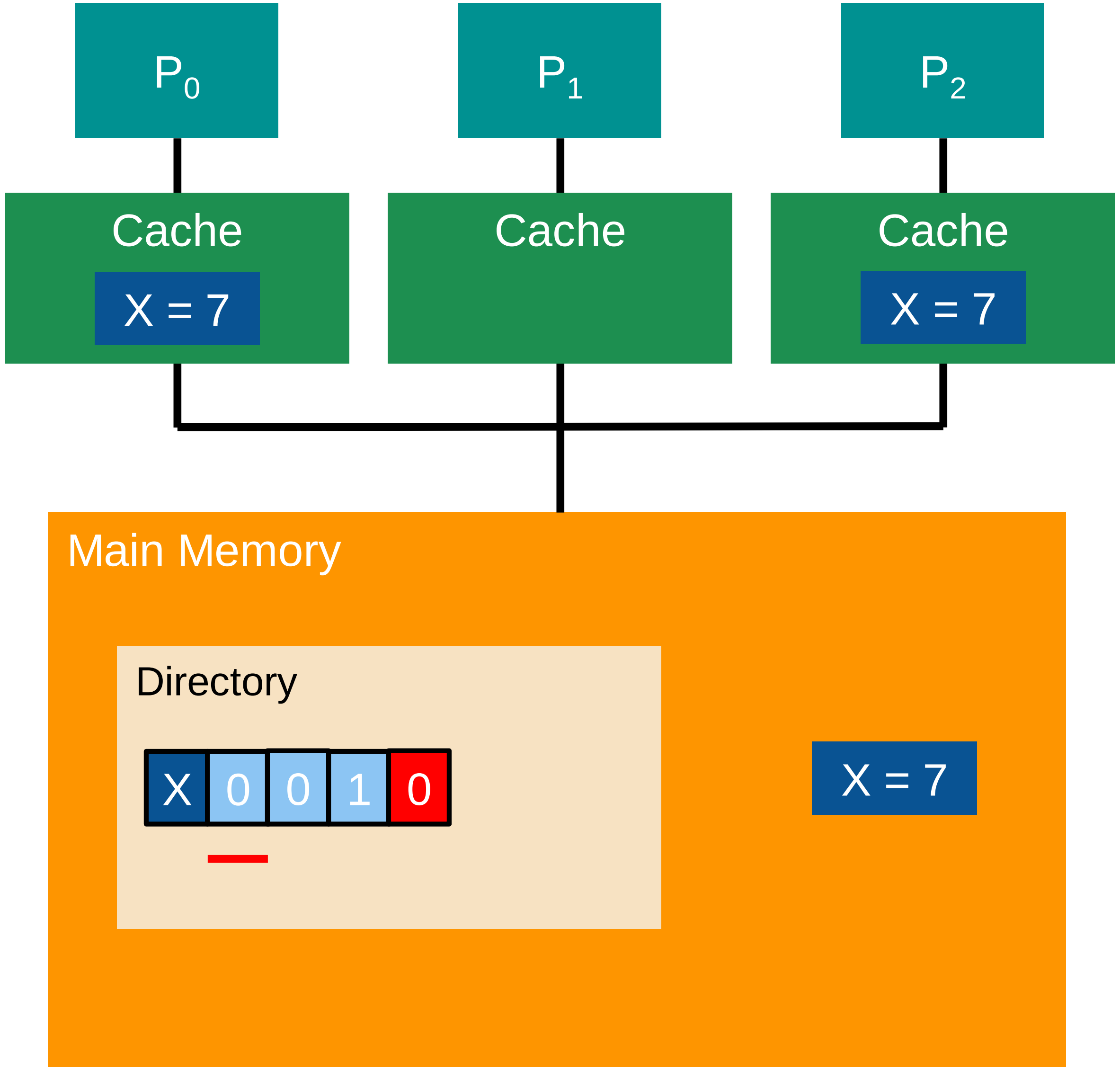
Directory-based CC: Read miss

- P_0 intends to read, misses
- If dirty bit (in directory) is off
  - Read from main memory



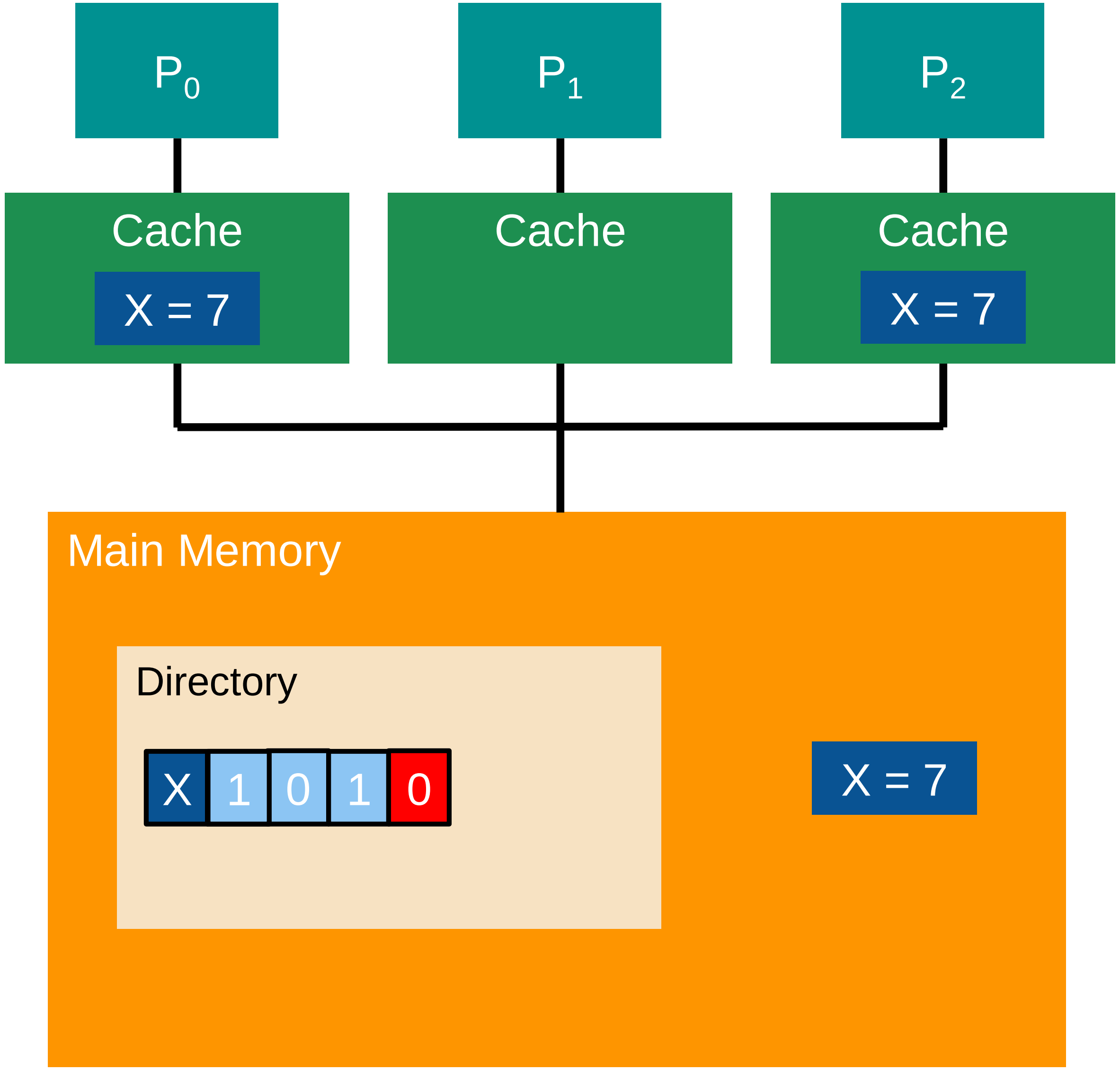
Directory-based CC: Read miss

- **P_0 intends to read, misses**
- **If dirty bit (in directory) is off**
  - Read from main memory
  - Set presence[i]



Directory-based CC: Read miss

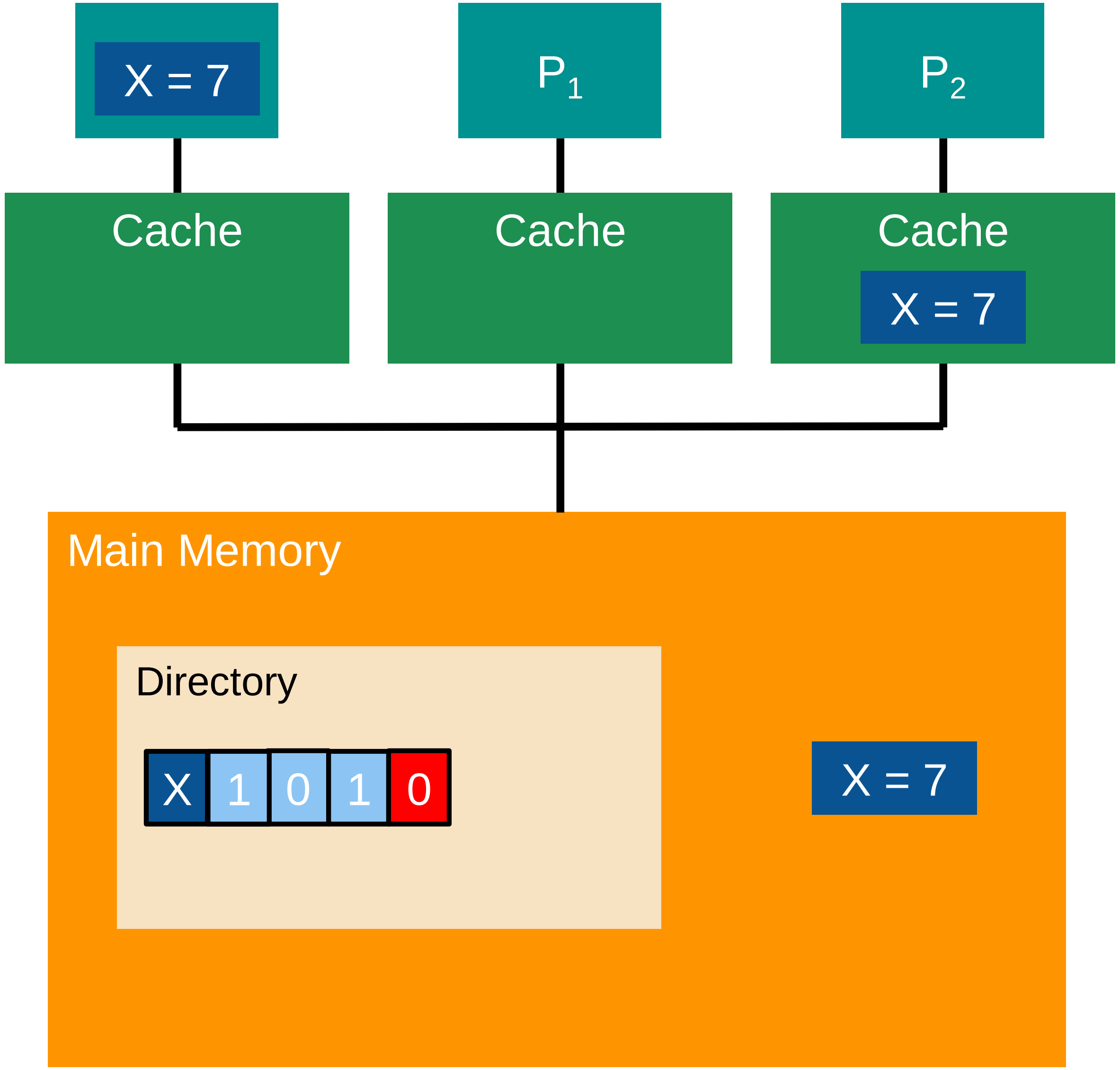
- **P_0 intends to read, misses**
- **If dirty bit (in directory) is off**
  - Read from main memory
  - Set presence[i]



Directory-based CC: Read miss

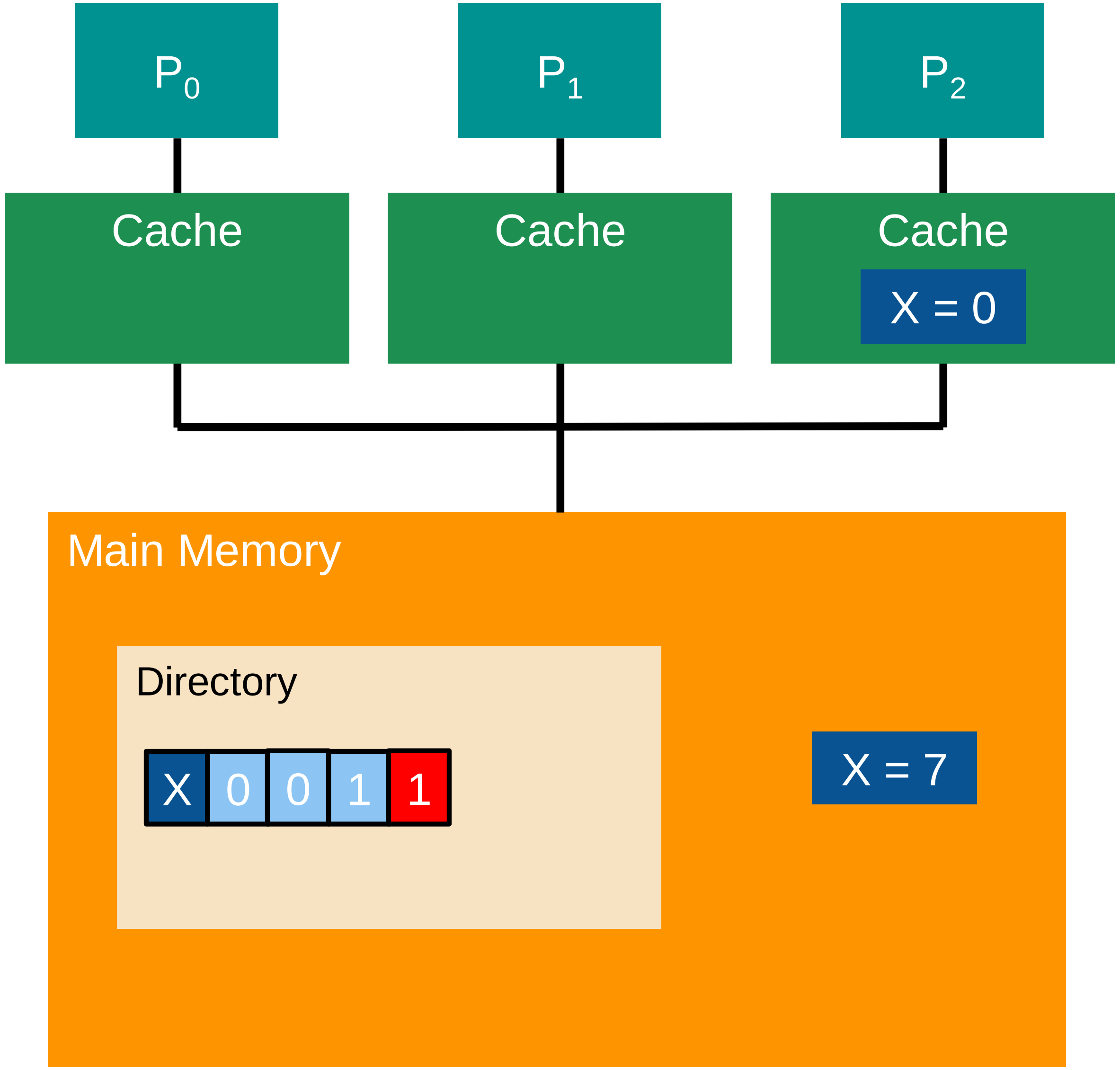
- P_0 intends to read, misses

- If dirty bit (in directory) is off
  - Read from main memory
  - Set presence[i]
  - Supply data to reader



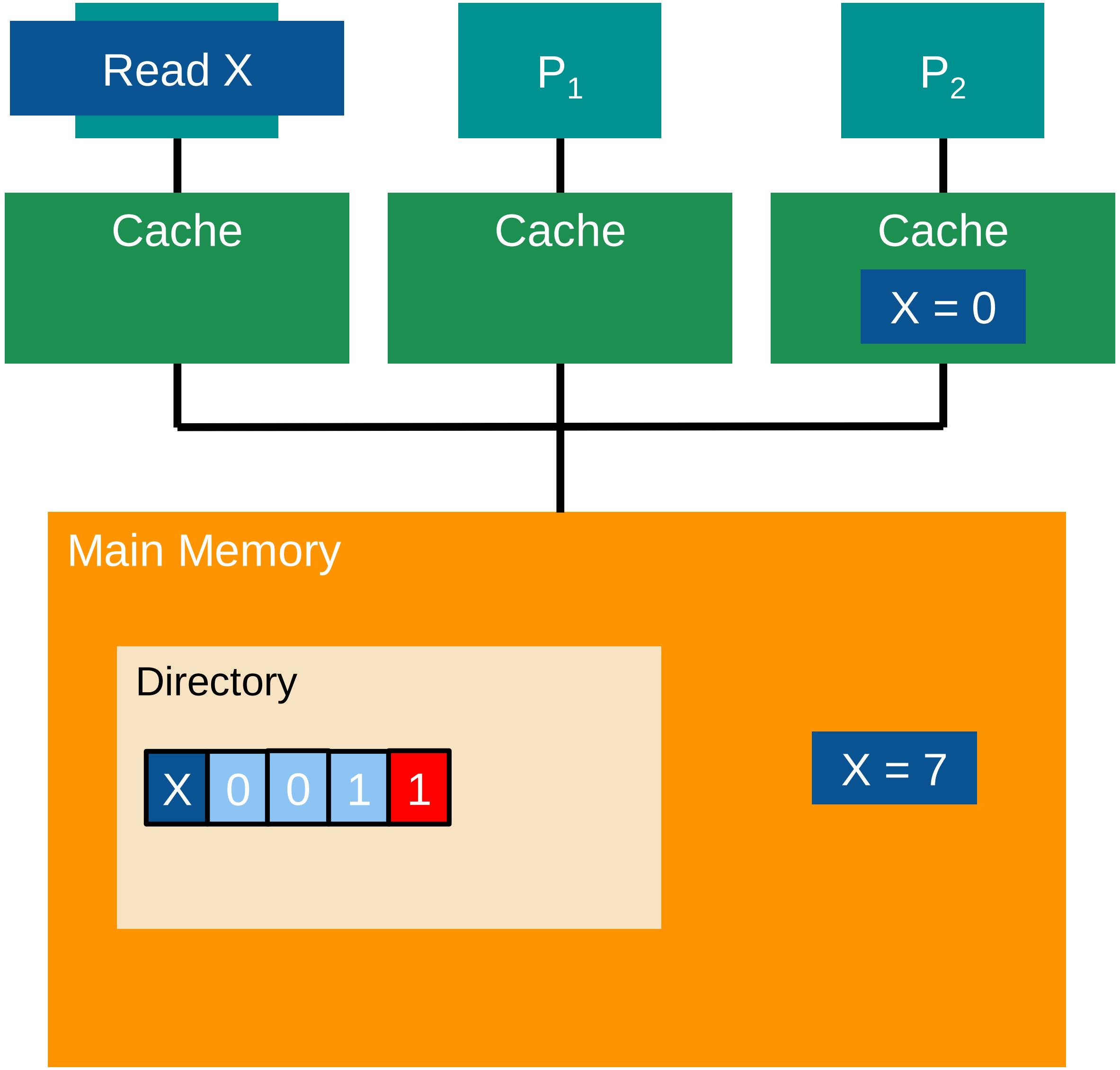
Directory-based CC: Read miss

- P_0 intends to read, misses



Directory-based CC: Read miss

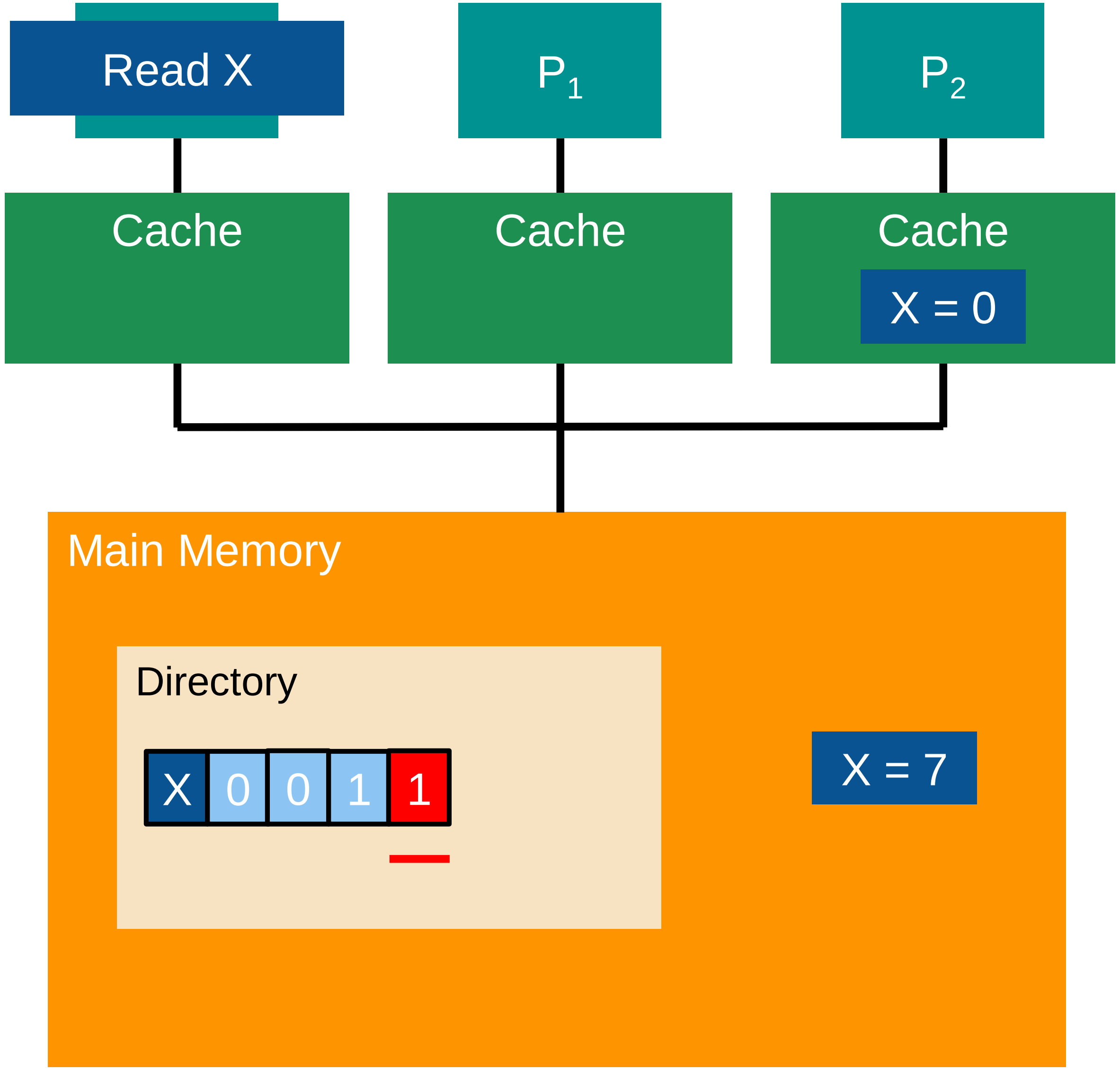
- P_0 intends to read, misses



Directory-based CC: Read miss

- P_0 intends to read, misses

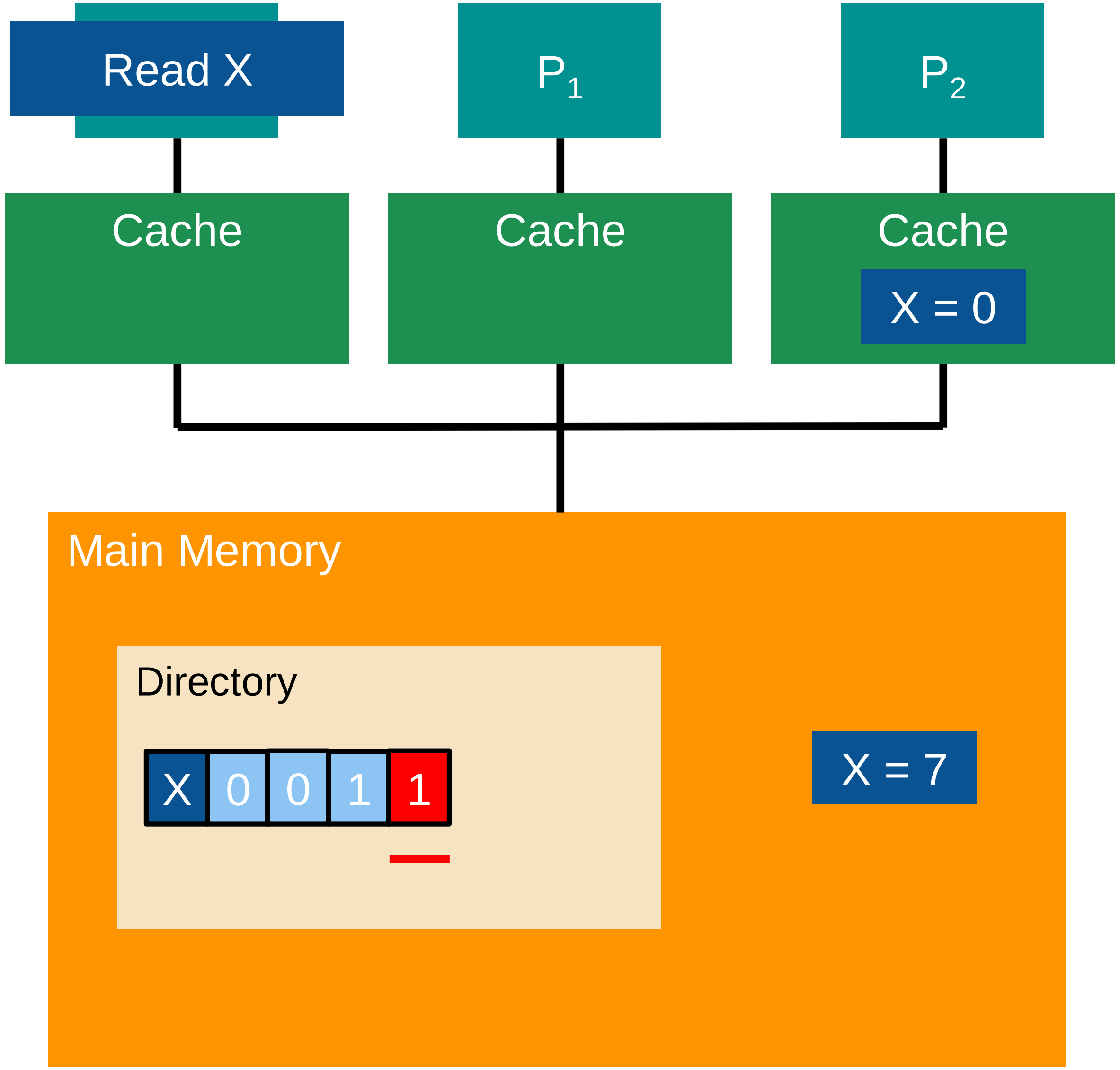
- If dirty bit is on



Directory-based CC: Read miss

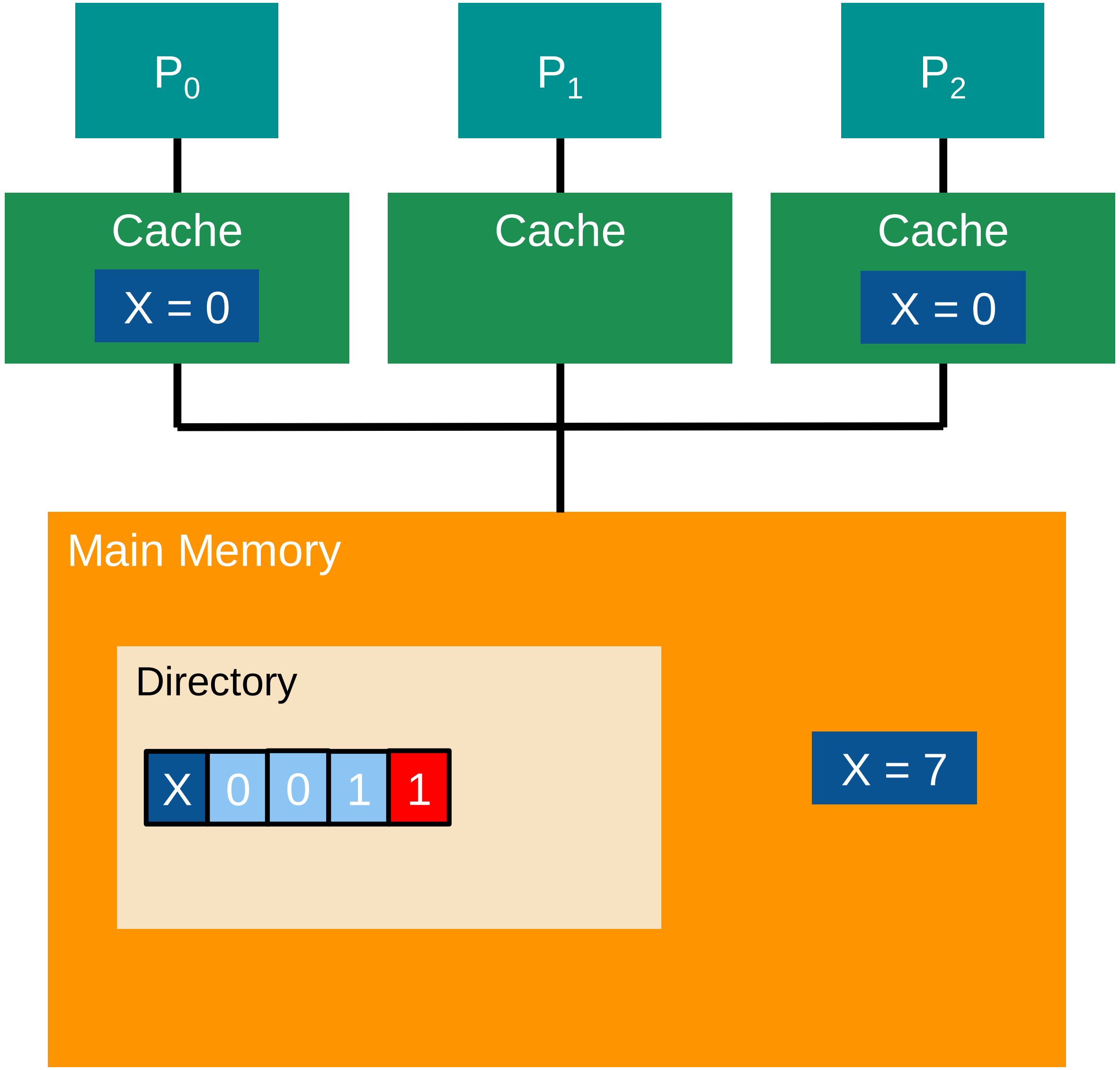
- **P_0 intends to read, misses**

- **If dirty bit is on**
  - Recall cache line from P_j (determine by presence[])



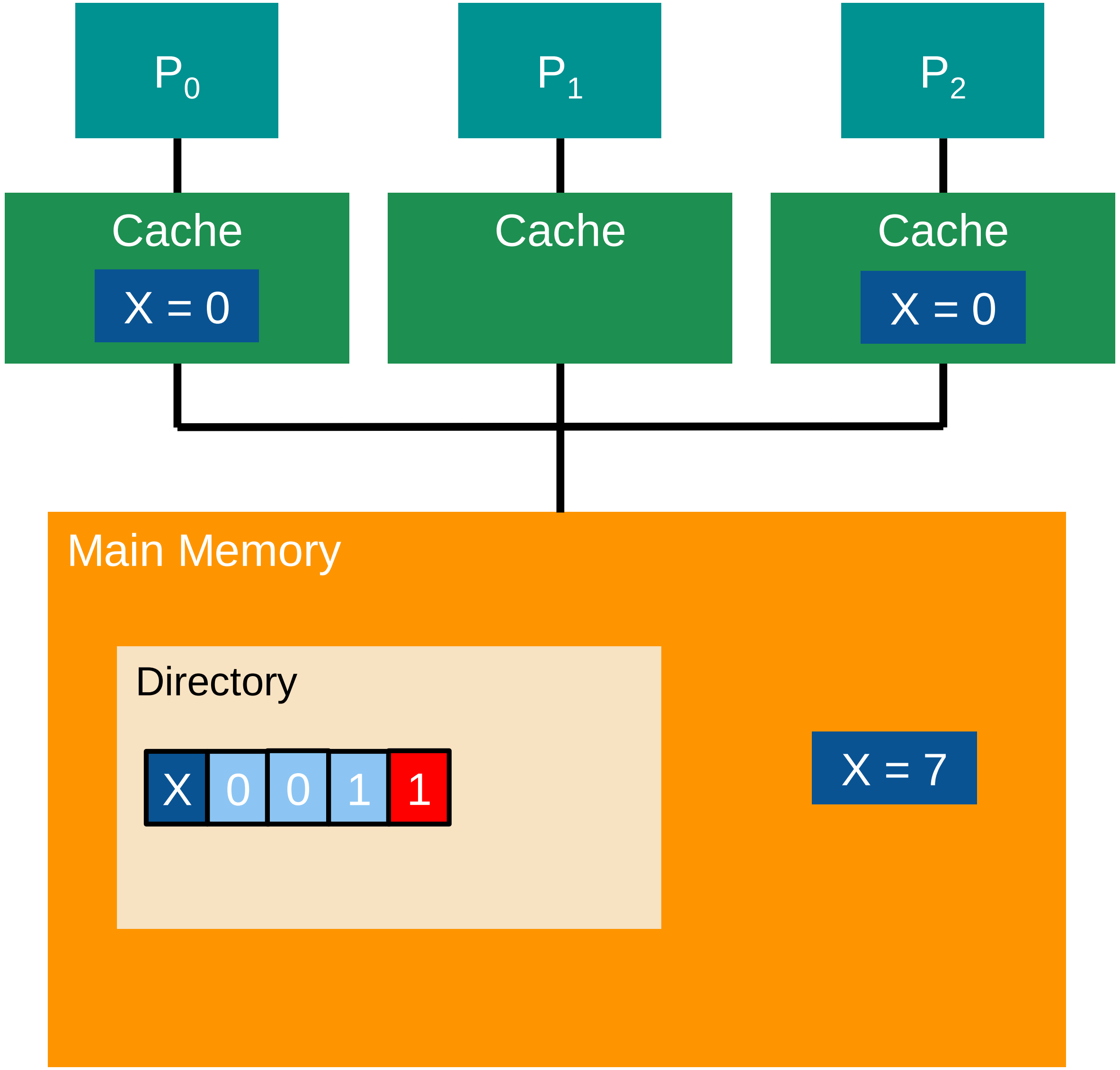
Directory-based CC: Read miss

- **P_0 intends to read, misses**
- **If dirty bit is on**
  - Recall cache line from P_j (determine by presence[])



Directory-based CC: Read miss

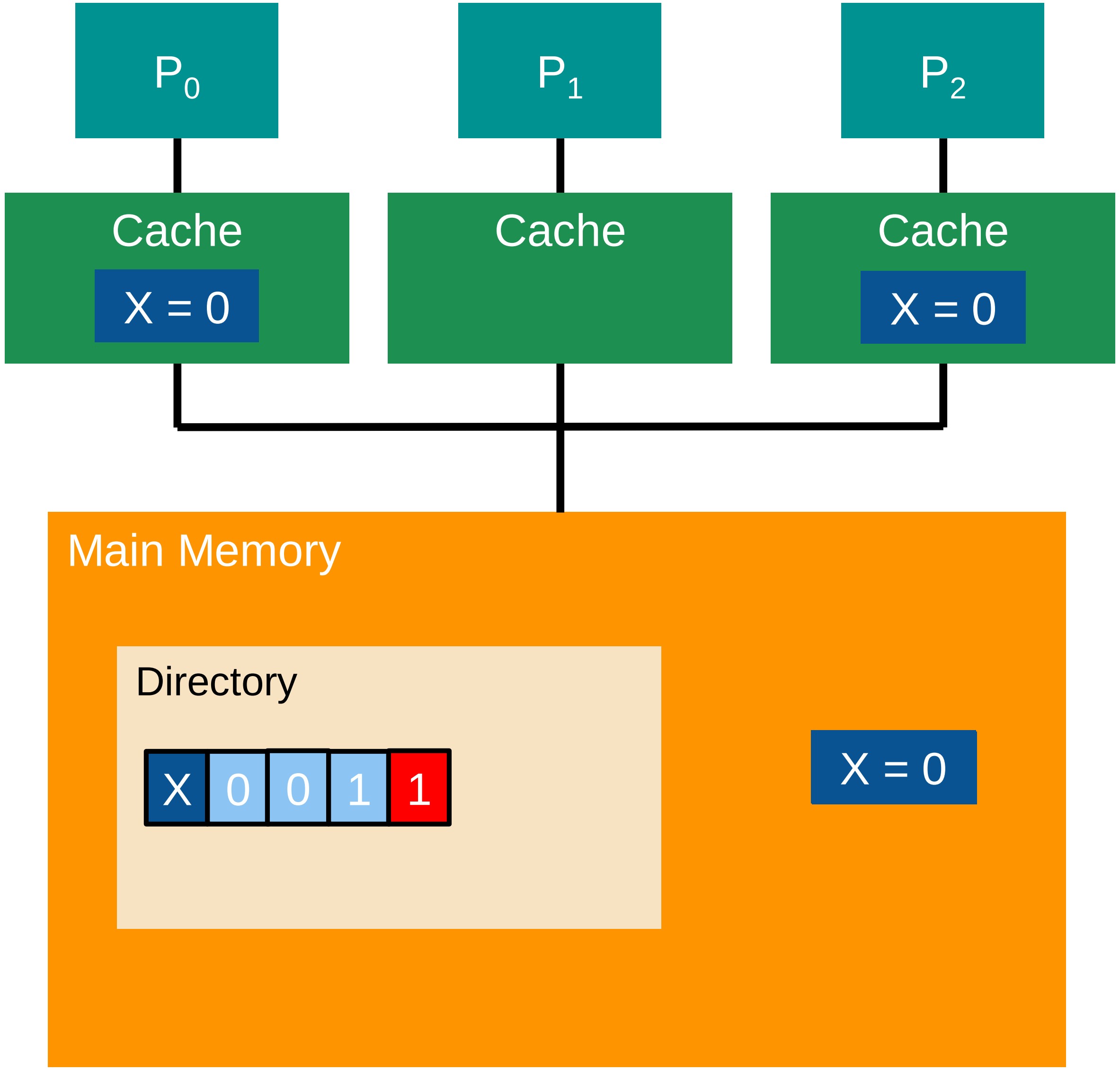
- **P_0 intends to read, misses**
- **If dirty bit is on**
  - Recall cache line from P_j (determine by presence[])
  - Update memory



Directory-based CC: Read miss

- **P_0 intends to read, misses**

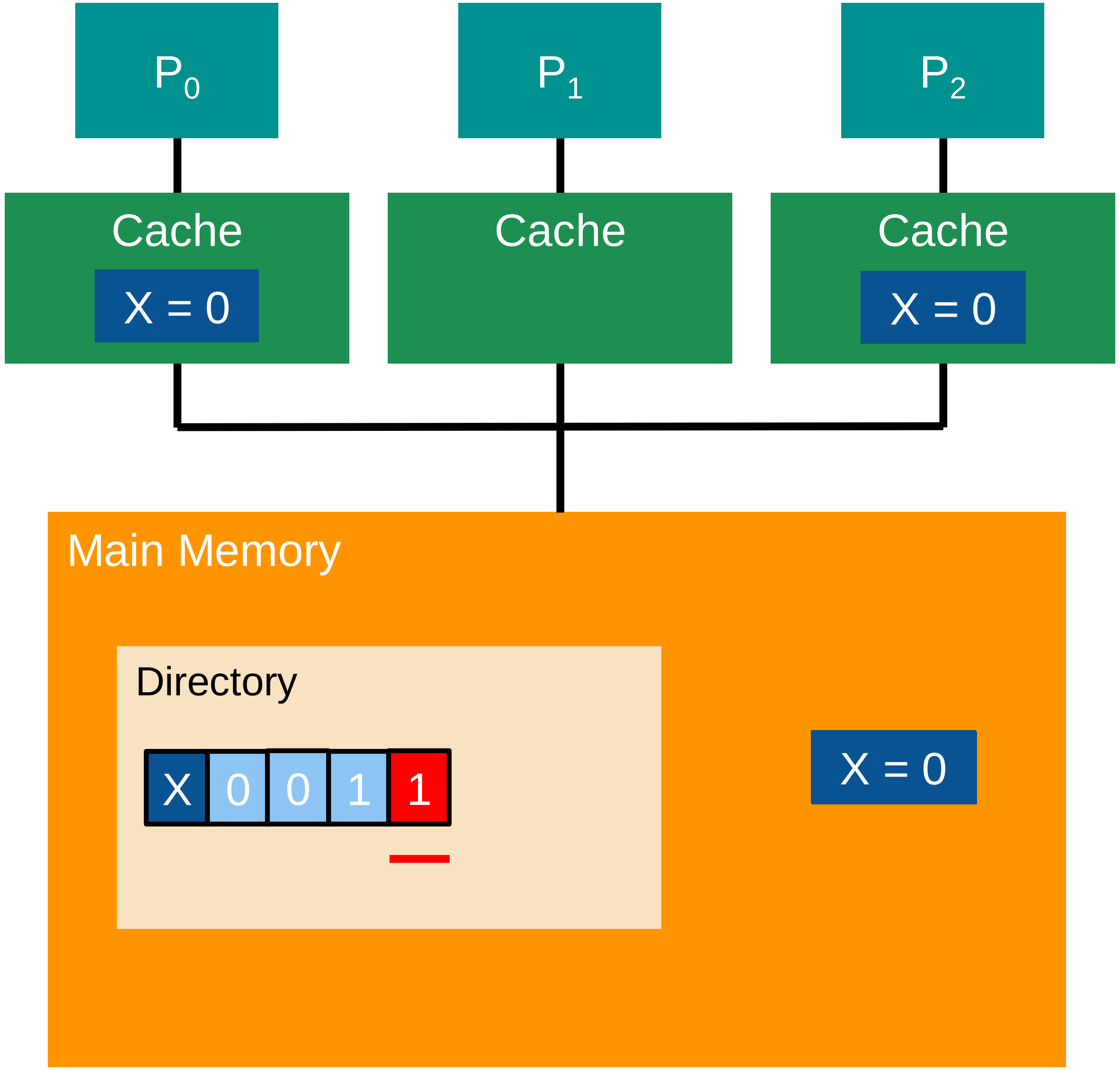
- **If dirty bit is on**
  - Recall cache line from P_j (determine by presence[])
  - Update memory



Directory-based CC: Read miss

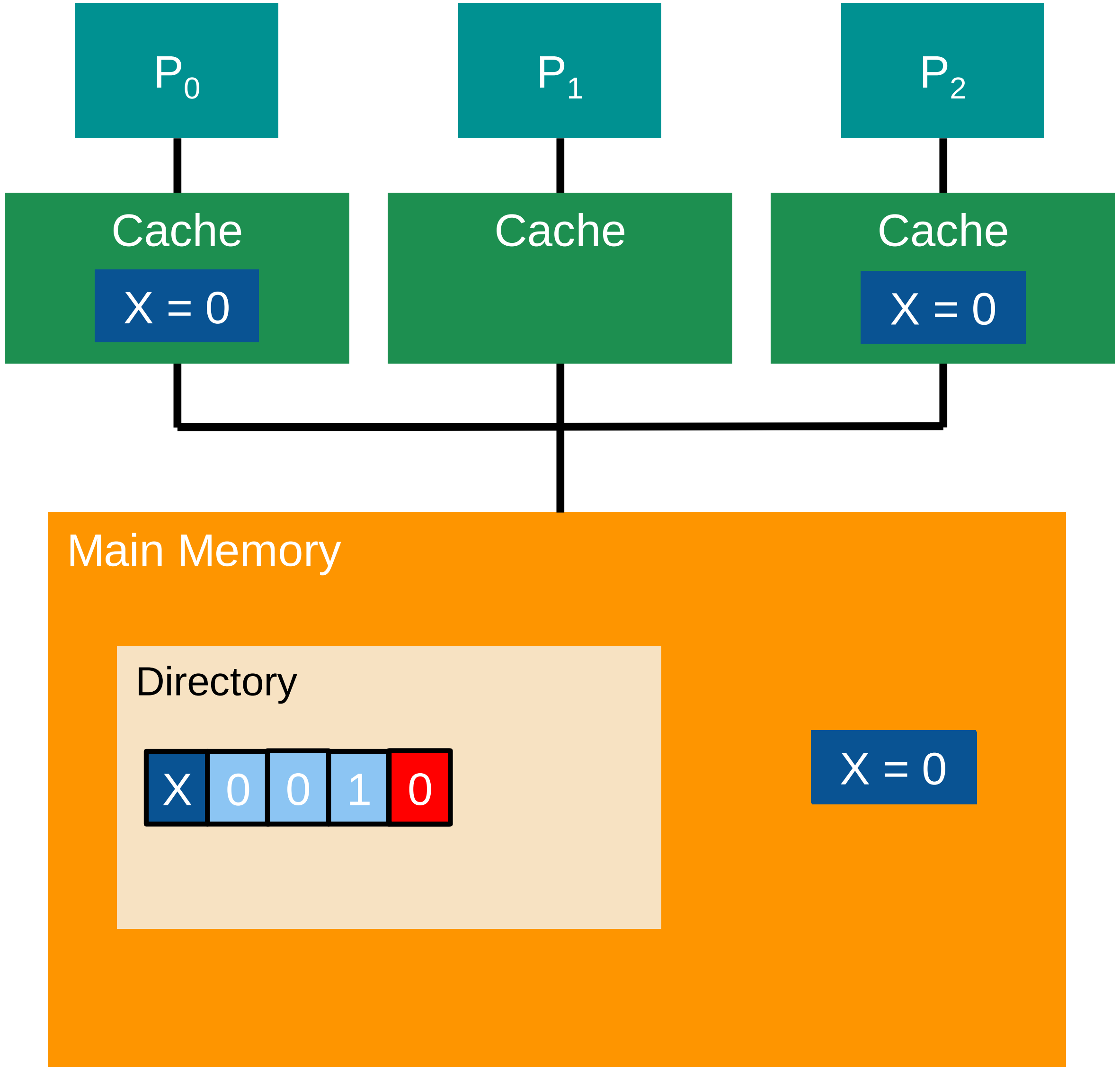
- **P_0 intends to read, misses**

- **If dirty bit is on**
  - Recall cache line from P_j (determine by presence[])
  - Update memory
  - Unset dirty bit, block shared



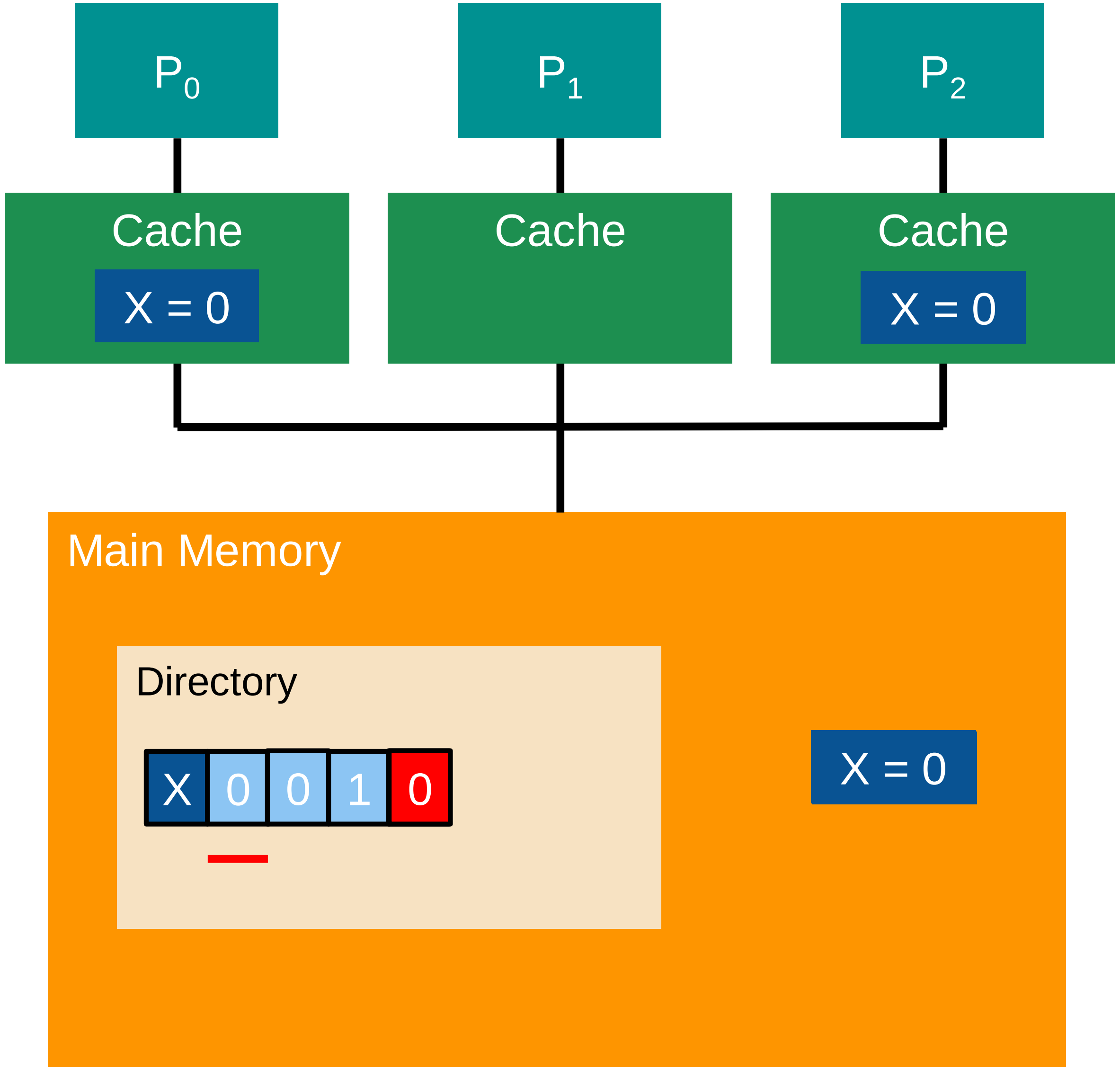
Directory-based CC: Read miss

- **P_0 intends to read, misses**
- **If dirty bit is on**
  - Recall cache line from P_j (determine by presence[])
  - Update memory
  - Unset dirty bit, block shared



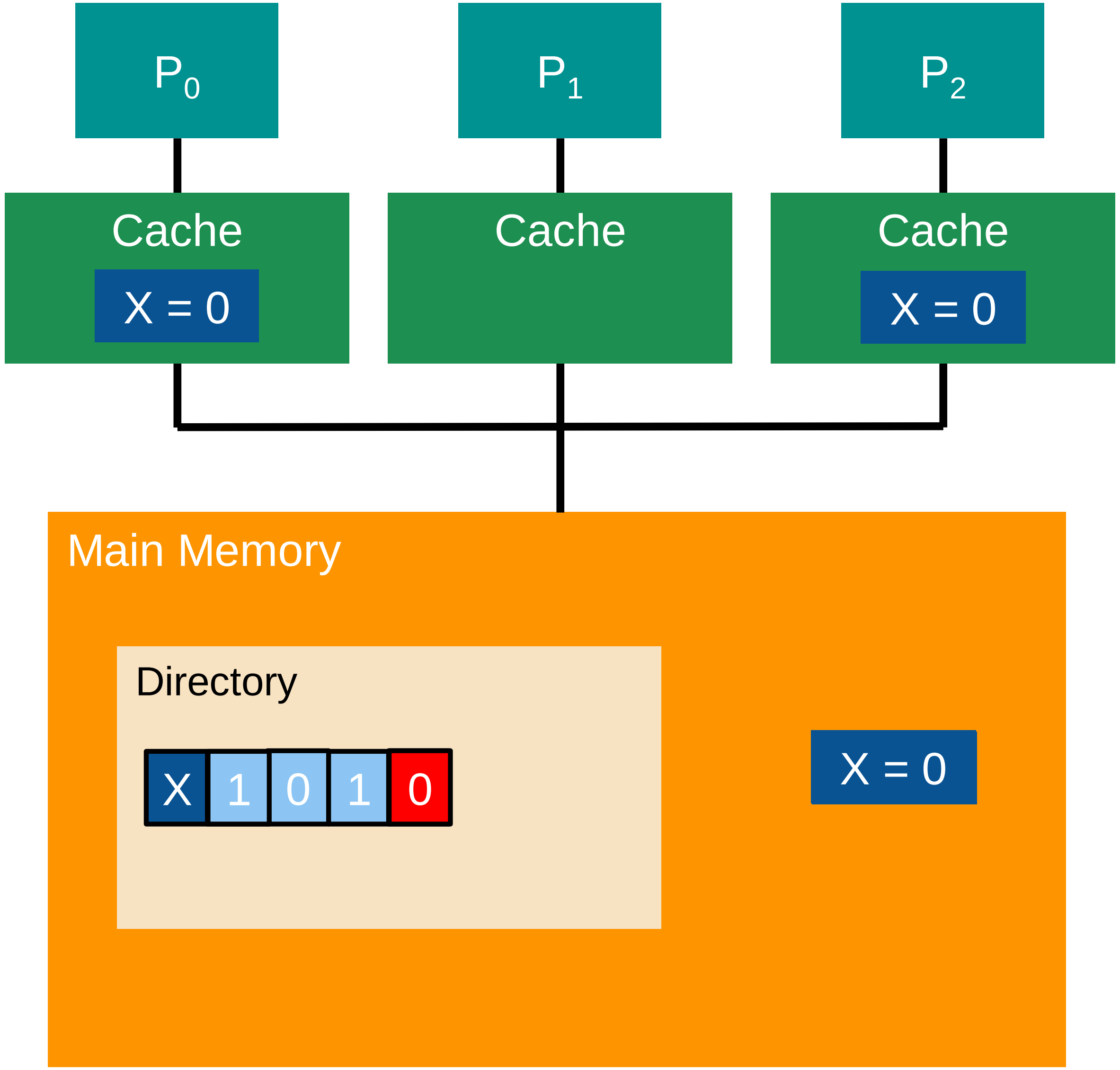
Directory-based CC: Read miss

- **P_0 intends to read, misses**
- **If dirty bit is on**
  - Recall cache line from P_j (determine by presence[])
  - Update memory
  - Unset dirty bit, block shared
  - Set presence[i]



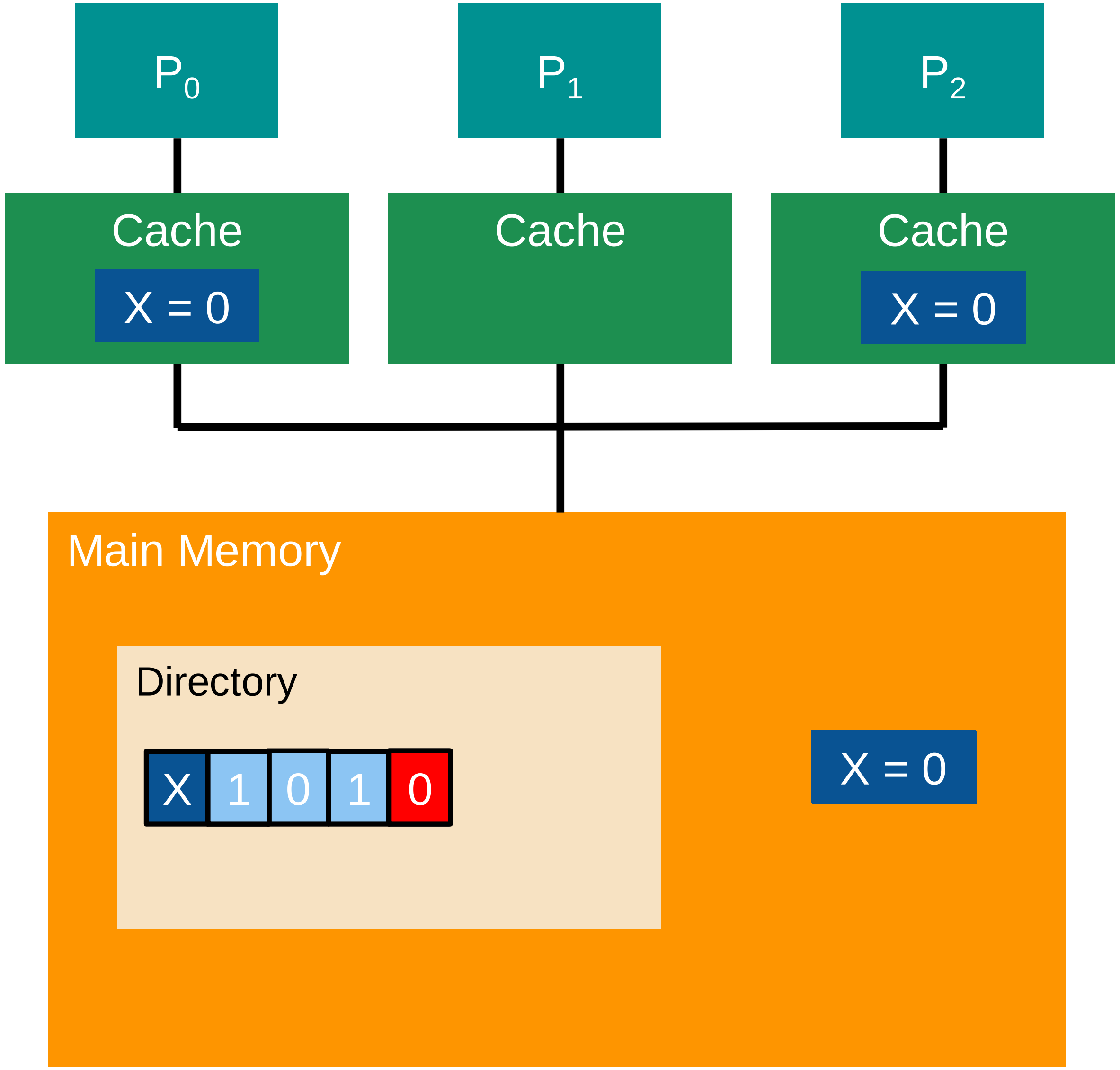
Directory-based CC: Read miss

- **P_0 intends to read, misses**
- **If dirty bit is on**
  - Recall cache line from P_j (determine by presence[])
  - Update memory
  - Unset dirty bit, block shared
  - Set presence[i]



Directory-based CC: Read miss

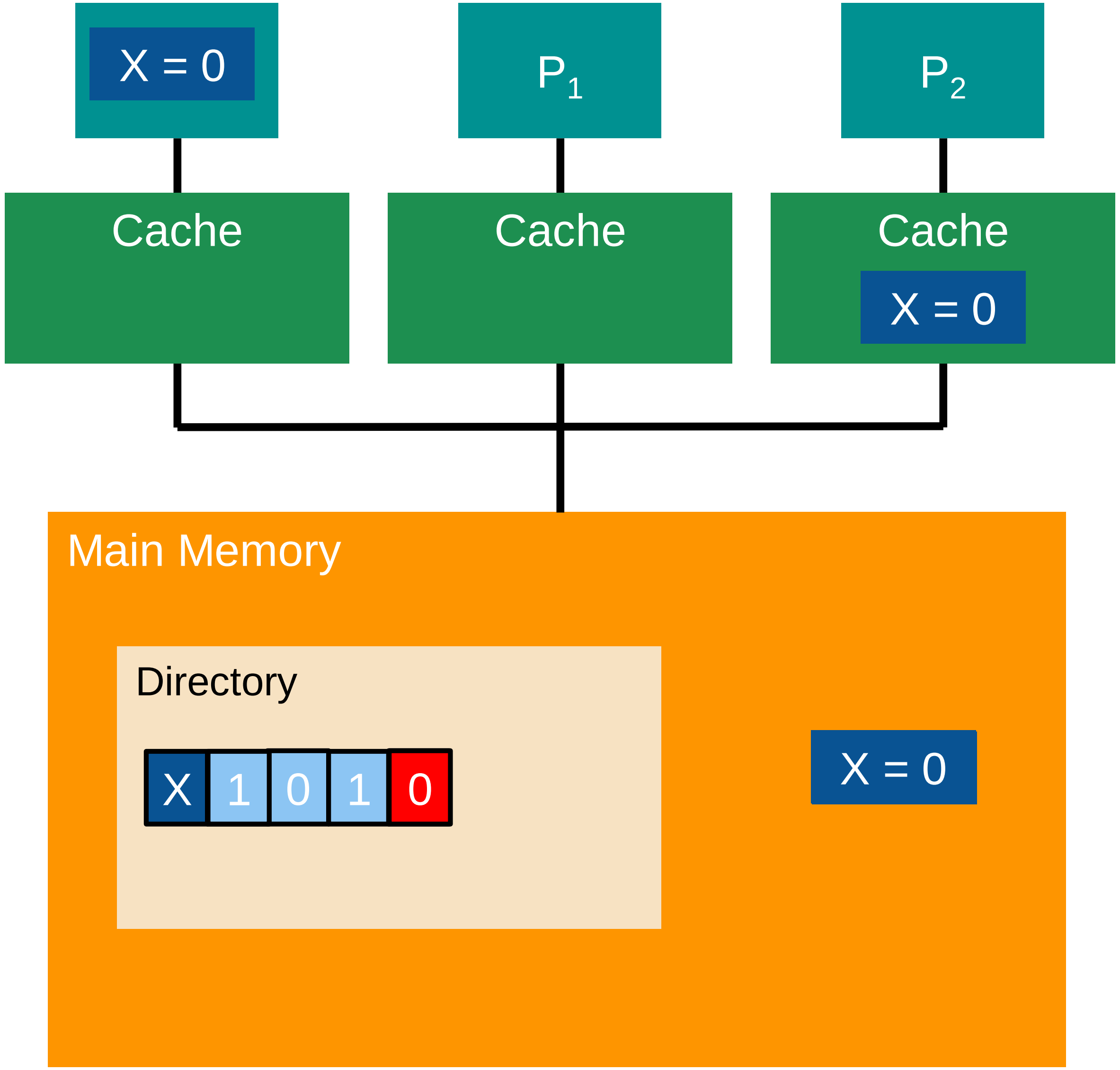
- **P_0 intends to read, misses**
- **If dirty bit is on**
  - Recall cache line from P_j (determine by presence[])
  - Update memory
  - Unset dirty bit, block shared
  - Set presence[i]
  - Supply data to reader



Directory-based CC: Read miss

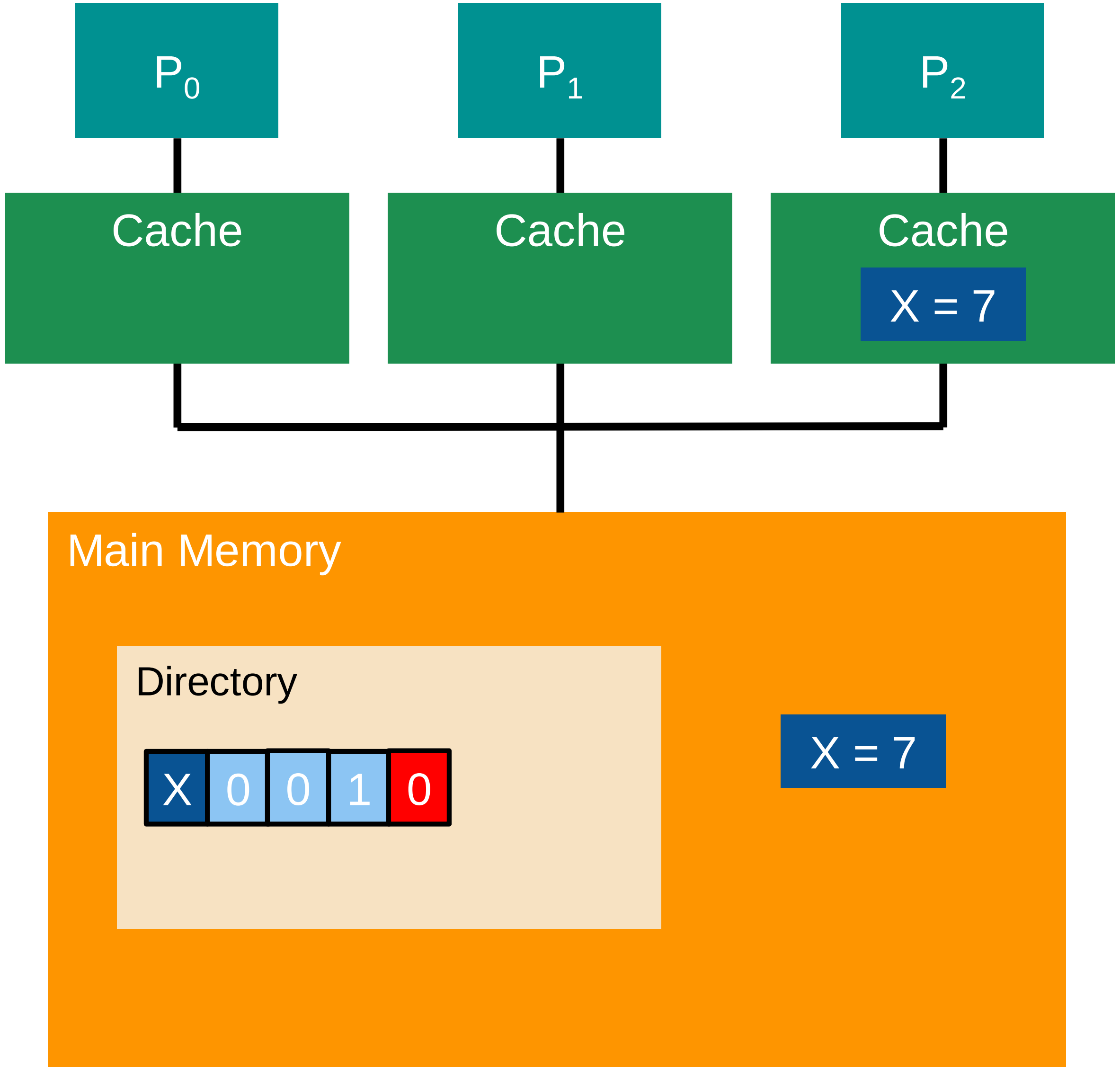
- **P_0 intends to read, misses**

- **If dirty bit is on**
  - Recall cache line from P_j (determine by presence[])
  - Update memory
  - Unset dirty bit, block shared
  - Set presence[i]
  - Supply data to reader



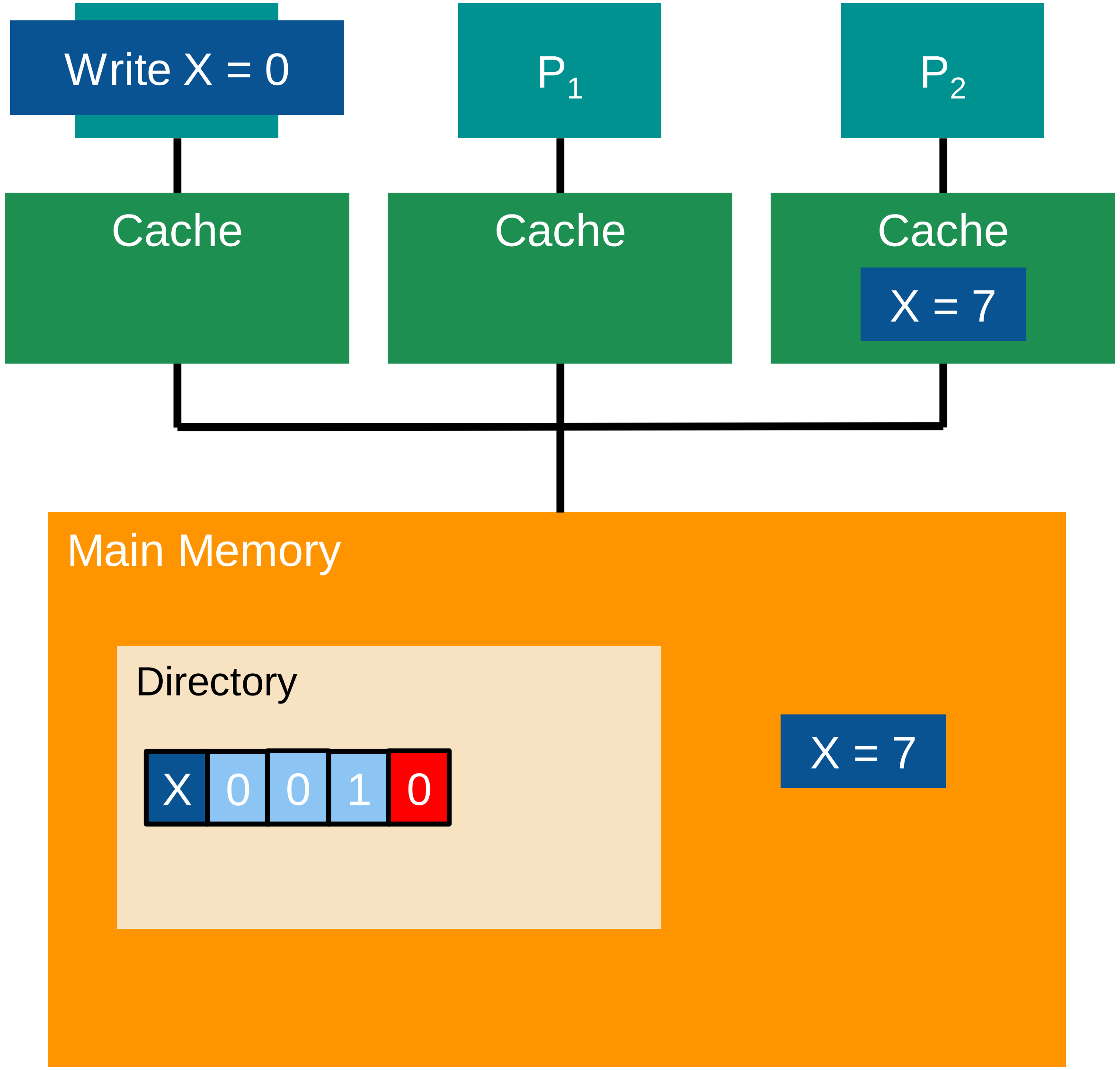
Directory-based CC: Write miss

- P_0 intends to write, misses



Directory-based CC: Write miss

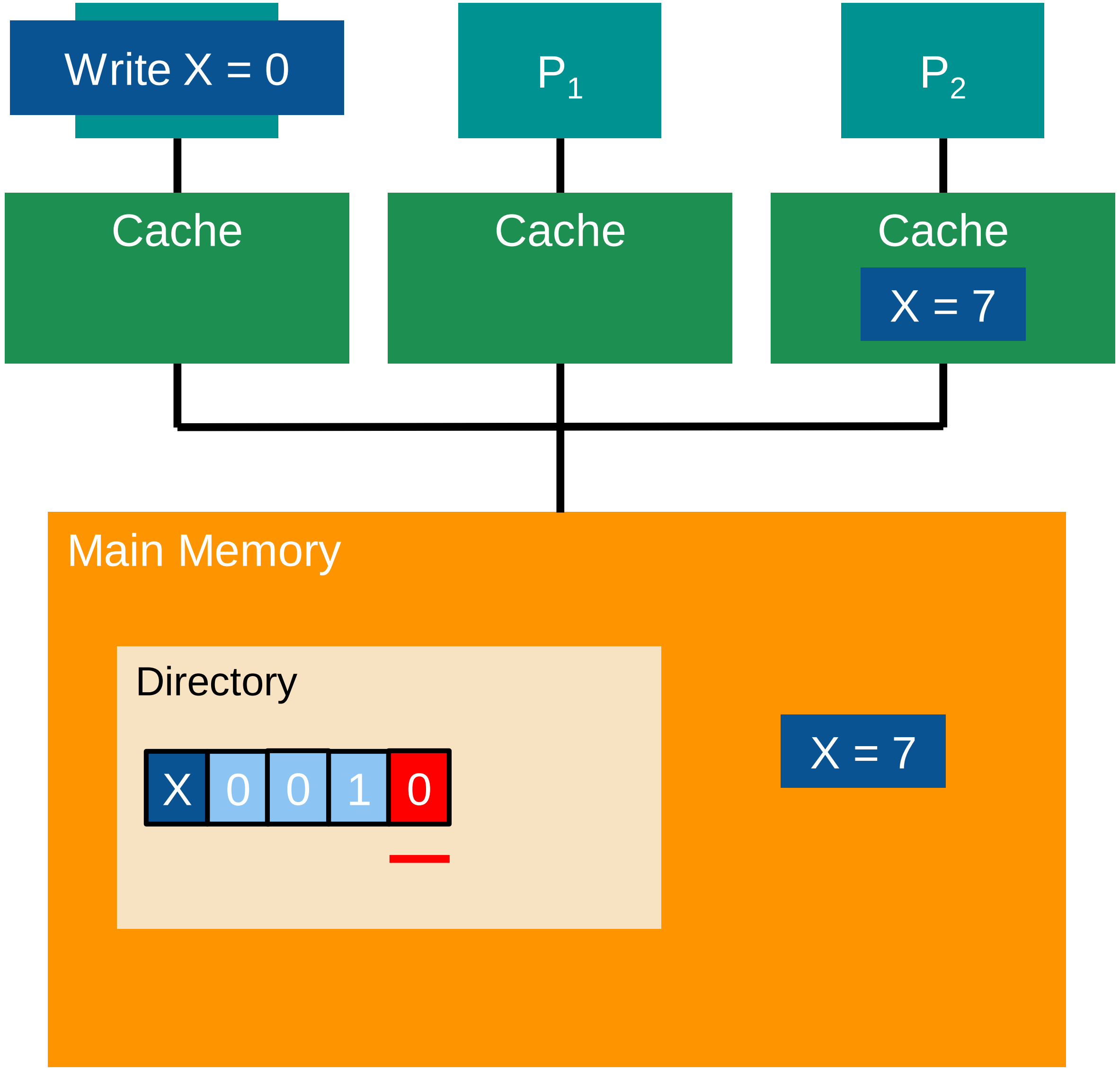
- P_0 intends to write, misses



Directory-based CC: Write miss

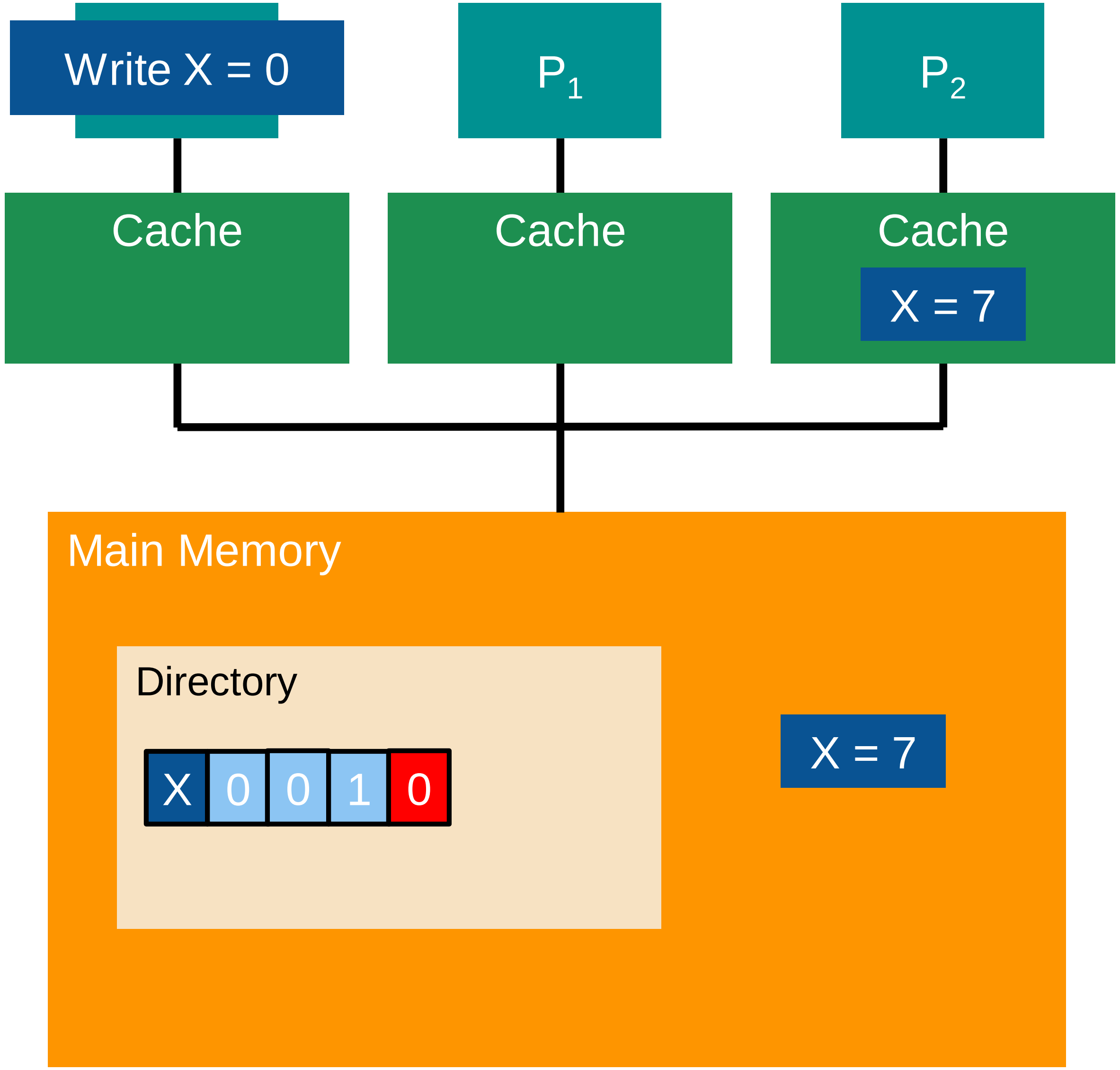
- P_0 intends to write, misses

- If dirty bit (in directory) is off



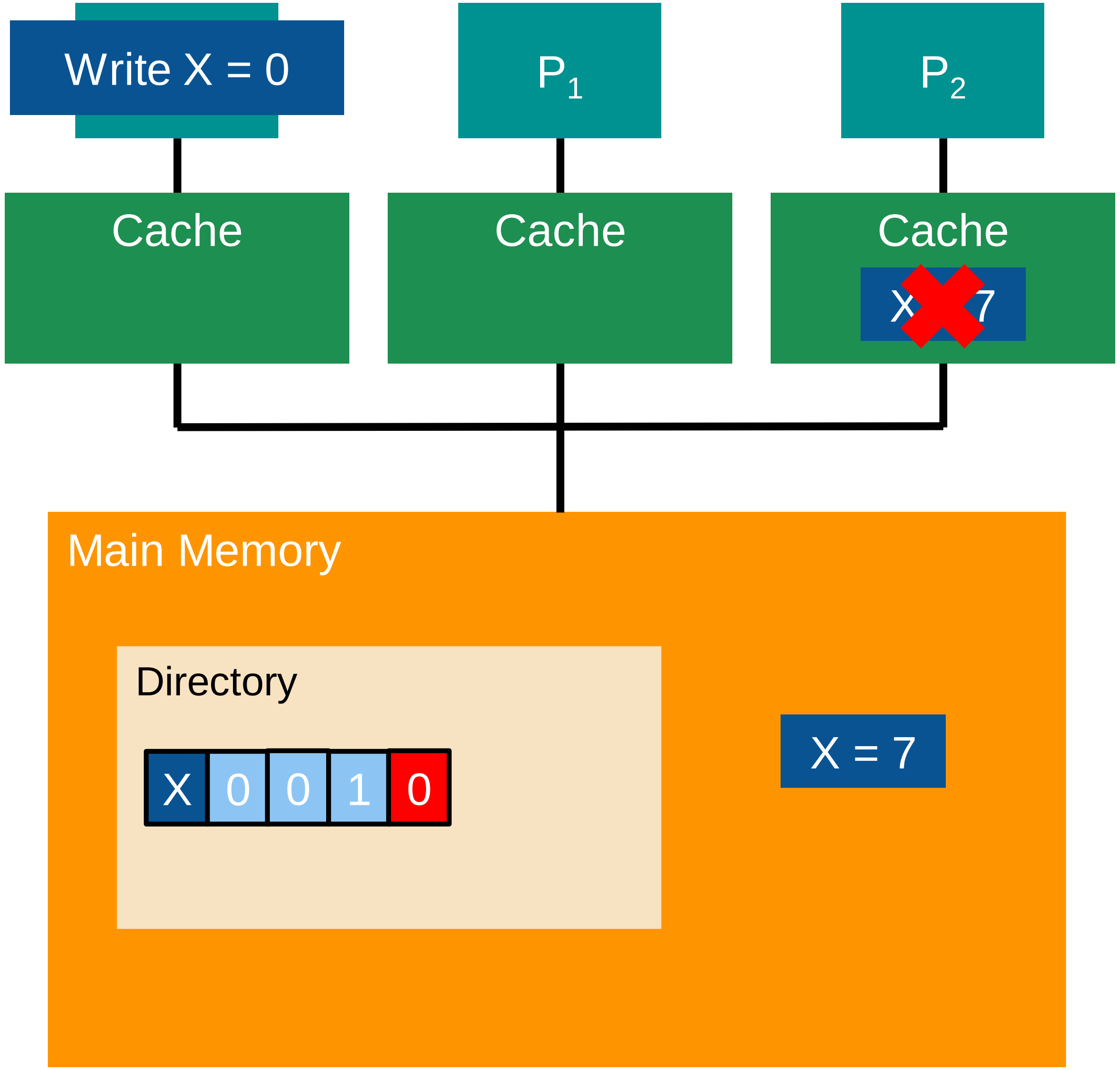
Directory-based CC: Write miss

- P_0 intends to write, misses
- If dirty bit (in directory) is off
  - Send invalidations to all processors P_j with presence[j] turned on



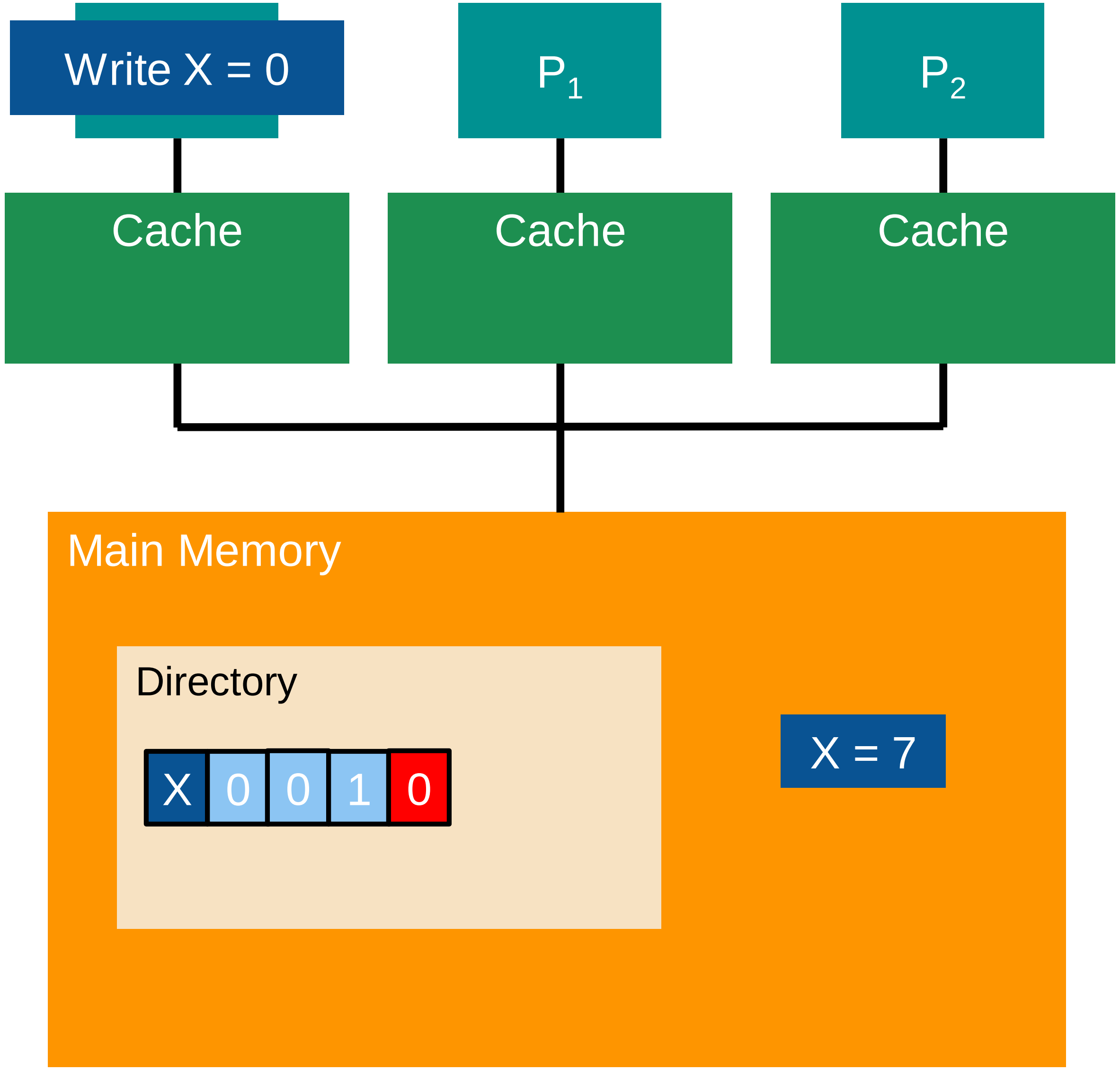
Directory-based CC: Write miss

- **P_0 intends to write, misses**
- **If dirty bit (in directory) is off**
  - Send invalidations to all processors P_j with presence[j] turned on



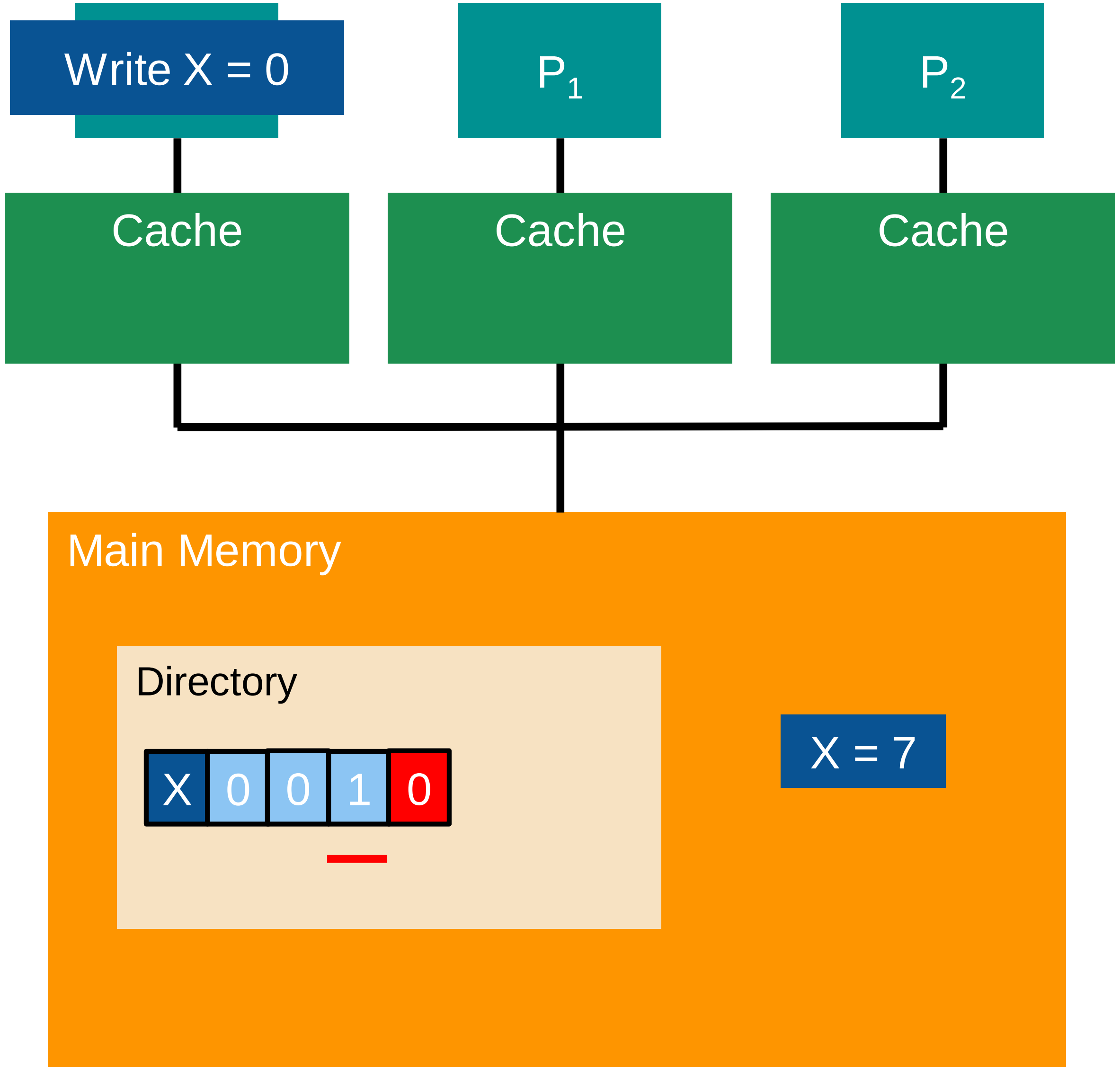
Directory-based CC: Write miss

- P_0 intends to write, misses
- If dirty bit (in directory) is off
  - Send invalidations to all processors P_j with presence[j] turned on



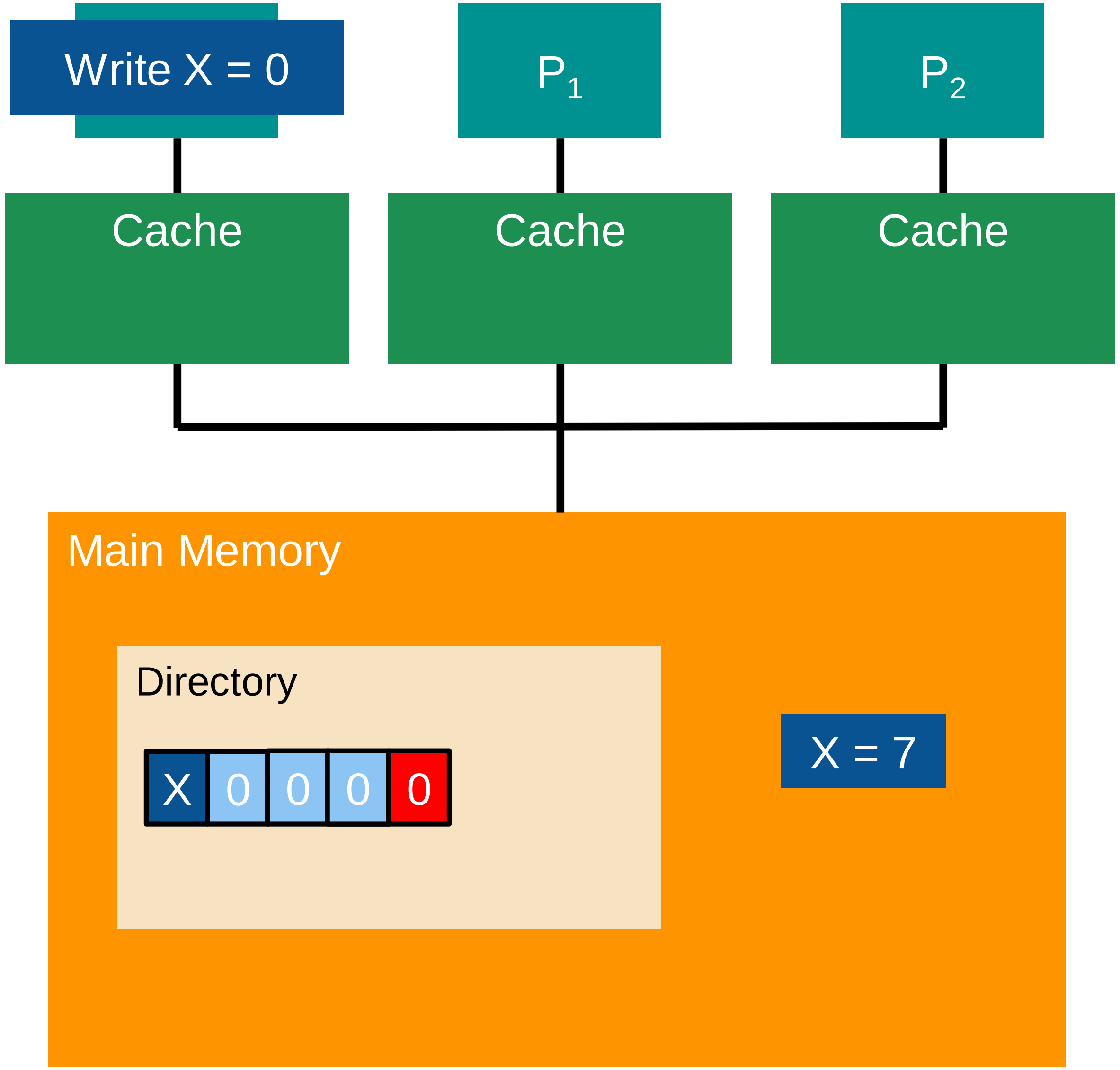
Directory-based CC: Write miss

- **P_0 intends to write, misses**
- **If dirty bit (in directory) is off**
  - Send invalidations to all processors P_j with presence[j] turned on
  - Unset presence bit for all processors



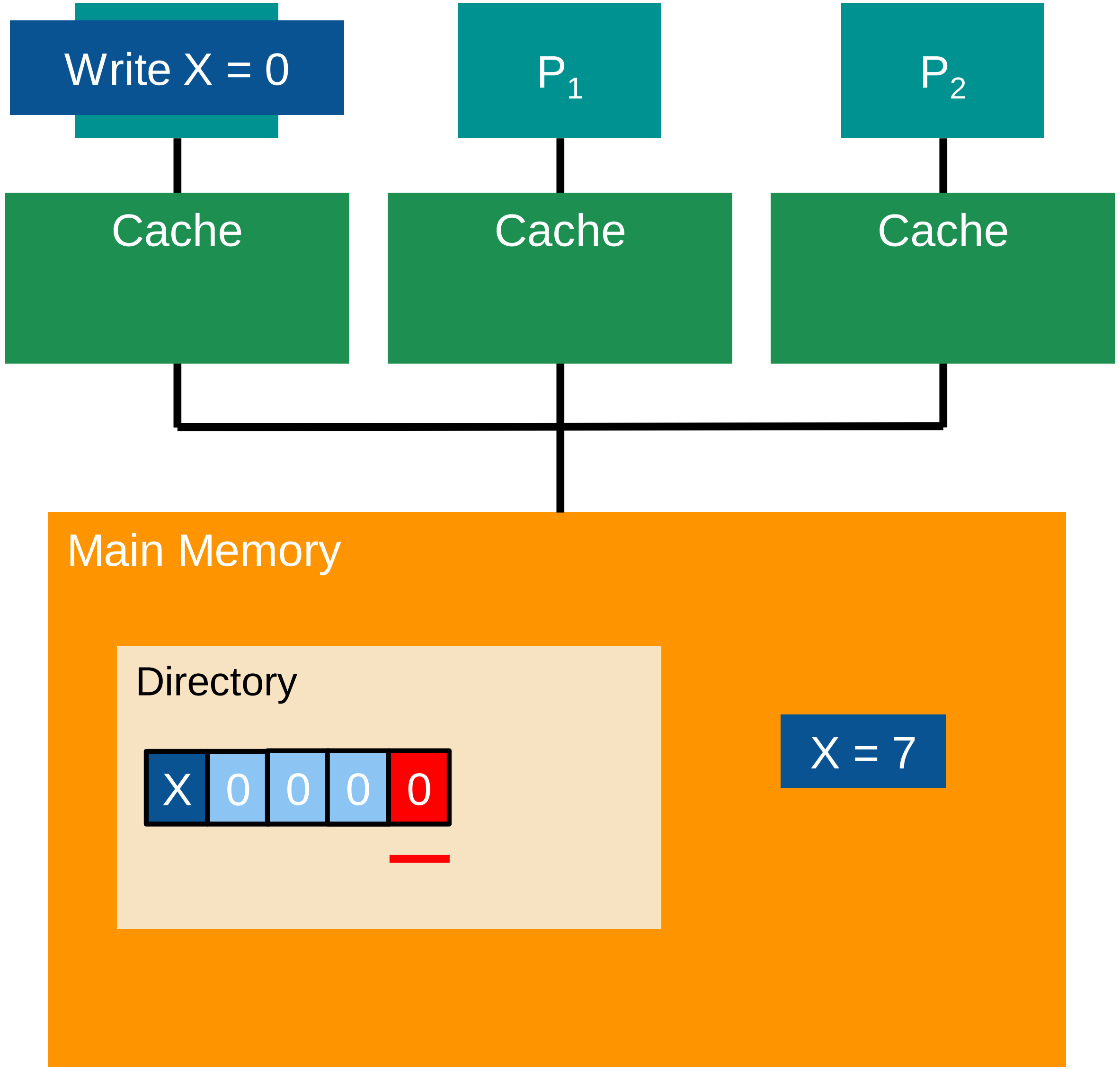
Directory-based CC: Write miss

- P_0 intends to write, misses
- If dirty bit (in directory) is off
  - Send invalidations to all processors P_j with presence[j] turned on
  - Unset presence bit for all processors



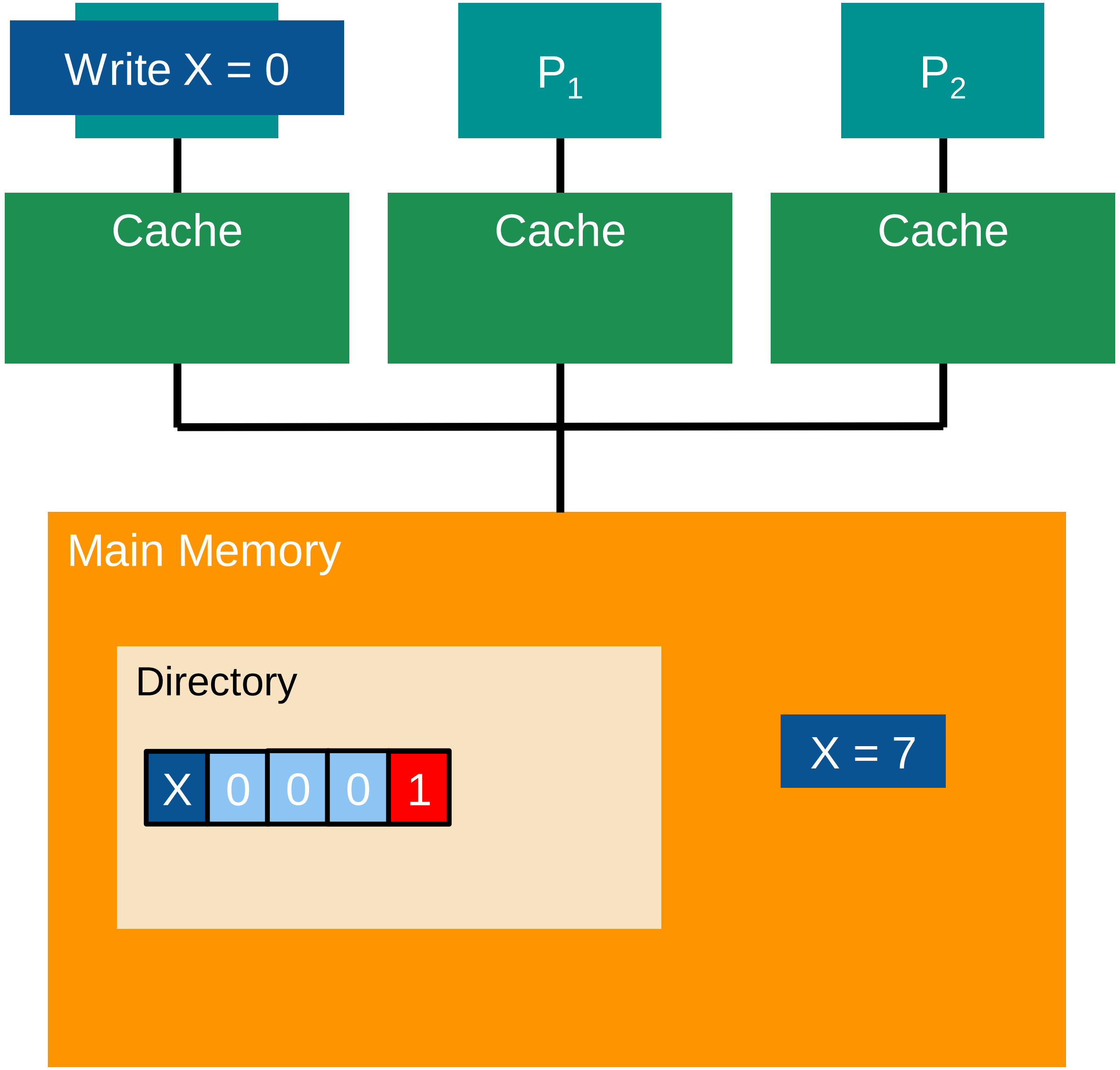
Directory-based CC: Write miss

- **P_0 intends to write, misses**
- **If dirty bit (in directory) is off**
  - Send invalidations to all processors P_j with presence[j] turned on
  - Unset presence bit for all processors
  - Set dirty bit



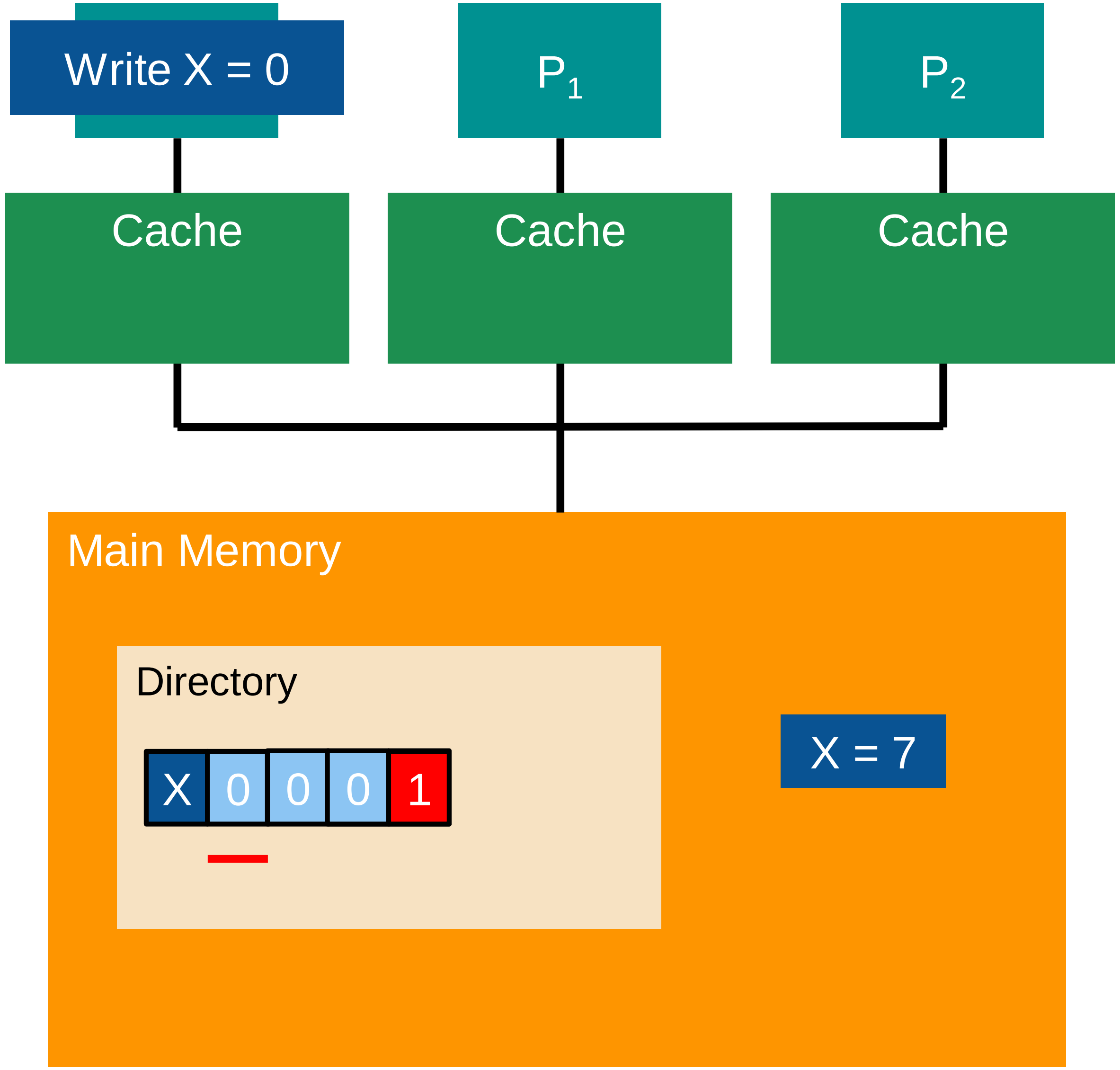
Directory-based CC: Write miss

- **P_0 intends to write, misses**
- **If dirty bit (in directory) is off**
  - Send invalidations to all processors P_j with presence[j] turned on
  - Unset presence bit for all processors
  - Set dirty bit



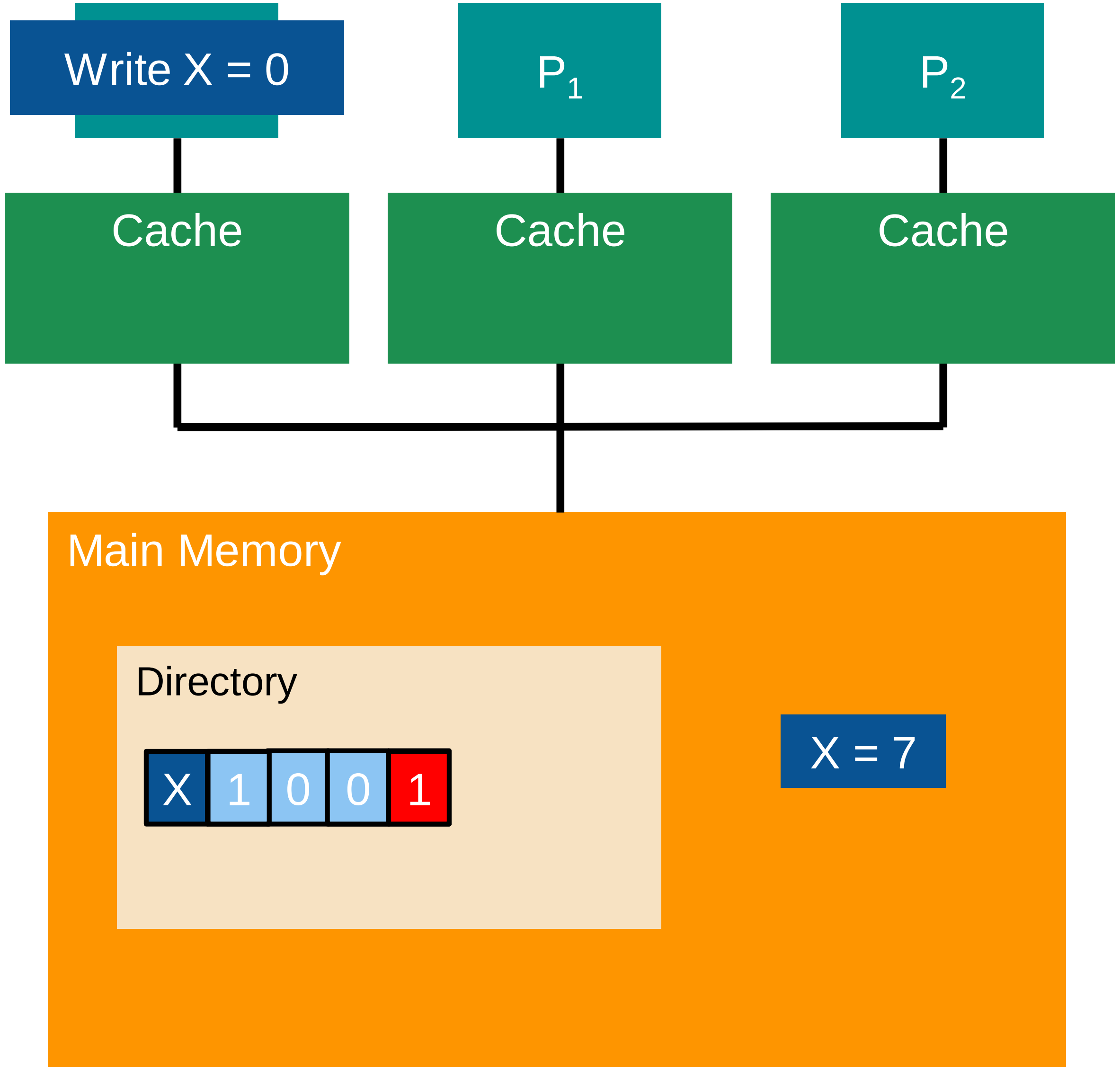
Directory-based CC: Write miss

- **P_0 intends to write, misses**
- **If dirty bit (in directory) is off**
  - Send invalidations to all processors P_j with presence[j] turned on
  - Unset presence bit for all processors
  - Set dirty bit
  - Set presence[i], owner P_i



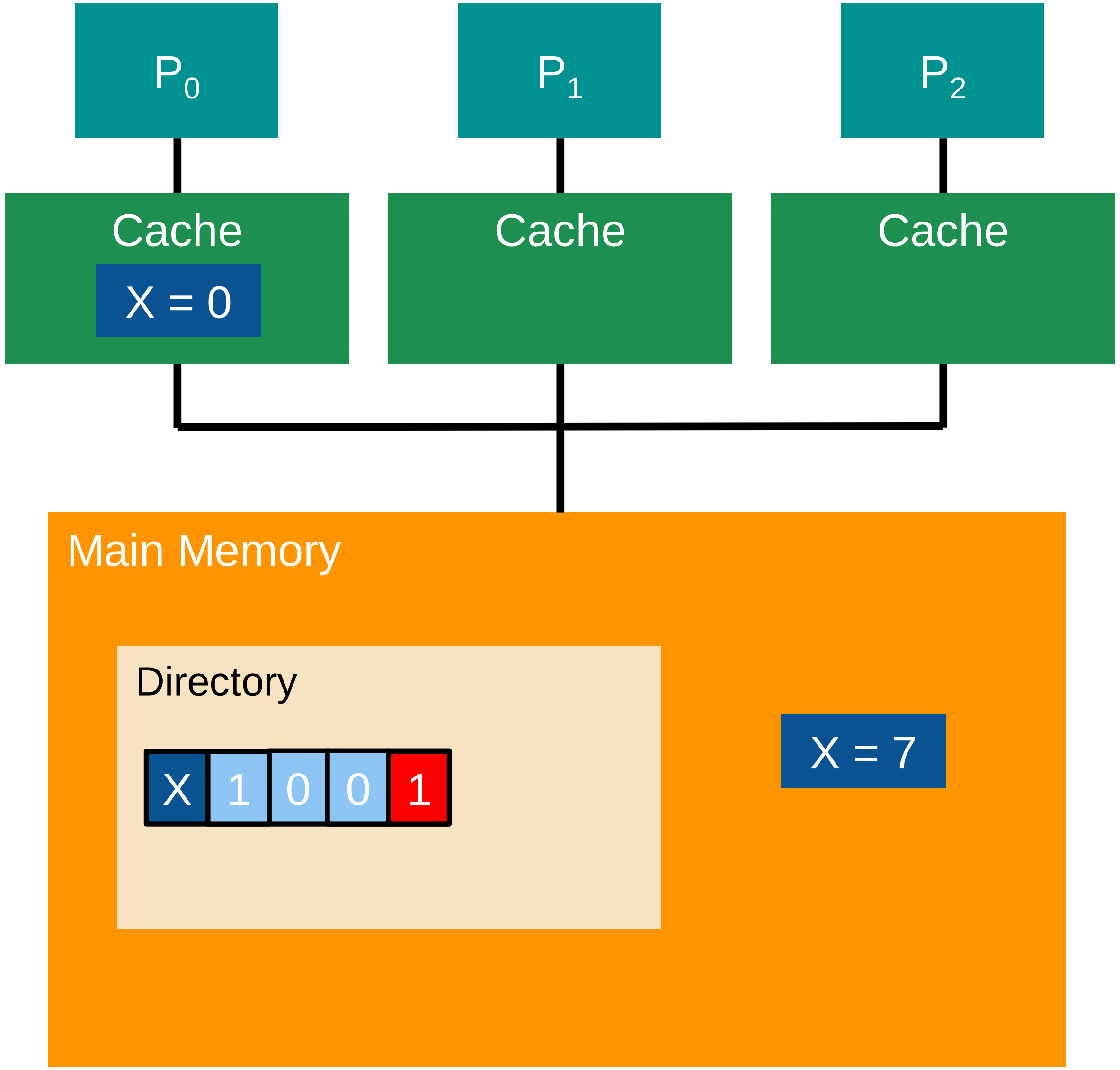
Directory-based CC: Write miss

- **P_0 intends to write, misses**
- **If dirty bit (in directory) is off**
  - Send invalidations to all processors P_j with presence[j] turned on
  - Unset presence bit for all processors
  - Set dirty bit
  - Set presence[i], owner P_i



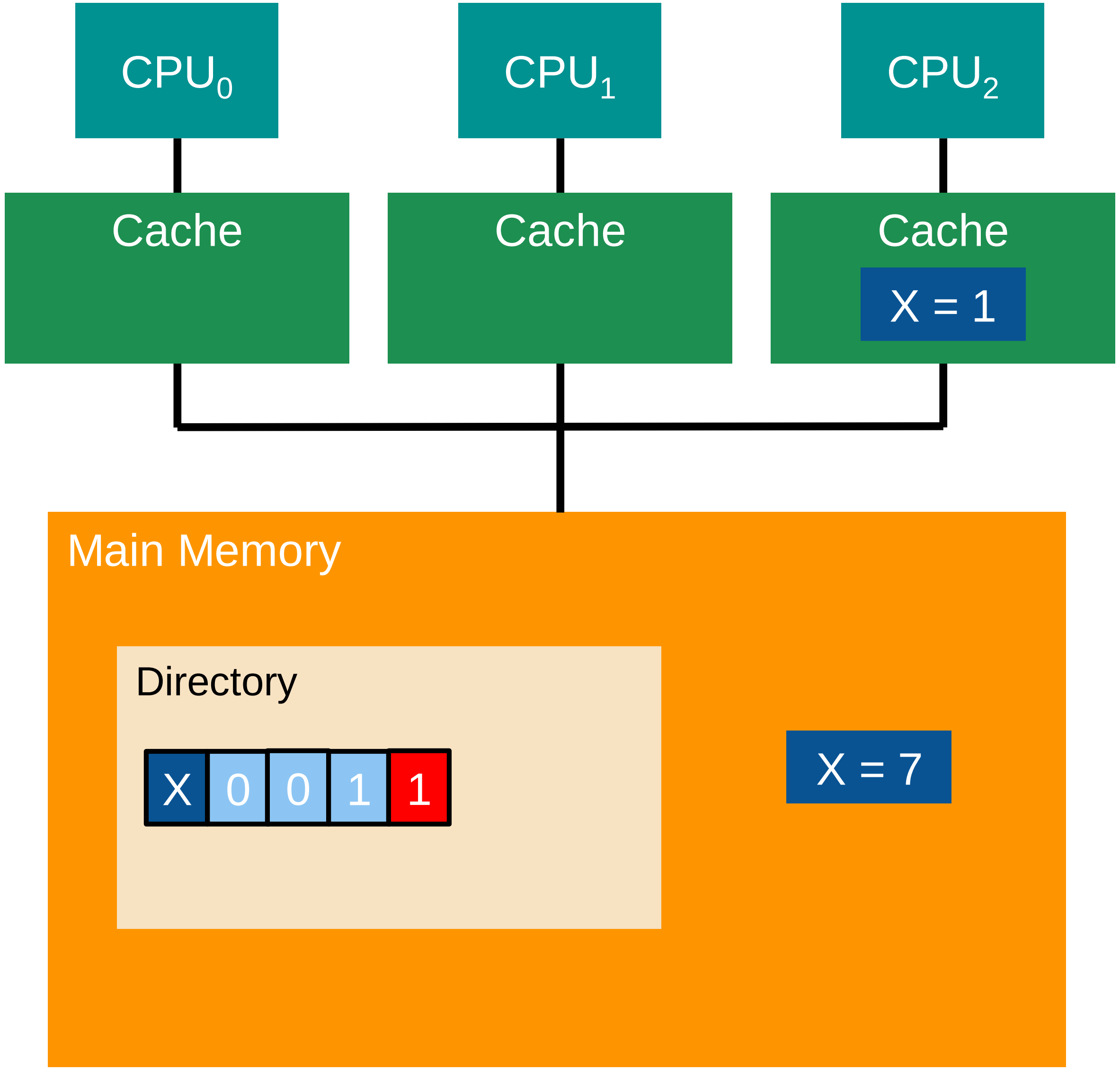
Directory-based CC: Write miss

- **P_0 intends to write, misses**
- **If dirty bit (in directory) is off**
  - Send invalidations to all processors P_j with presence[j] turned on
  - Unset presence bit for all processors
  - Set dirty bit
  - Set presence[i], owner P_i



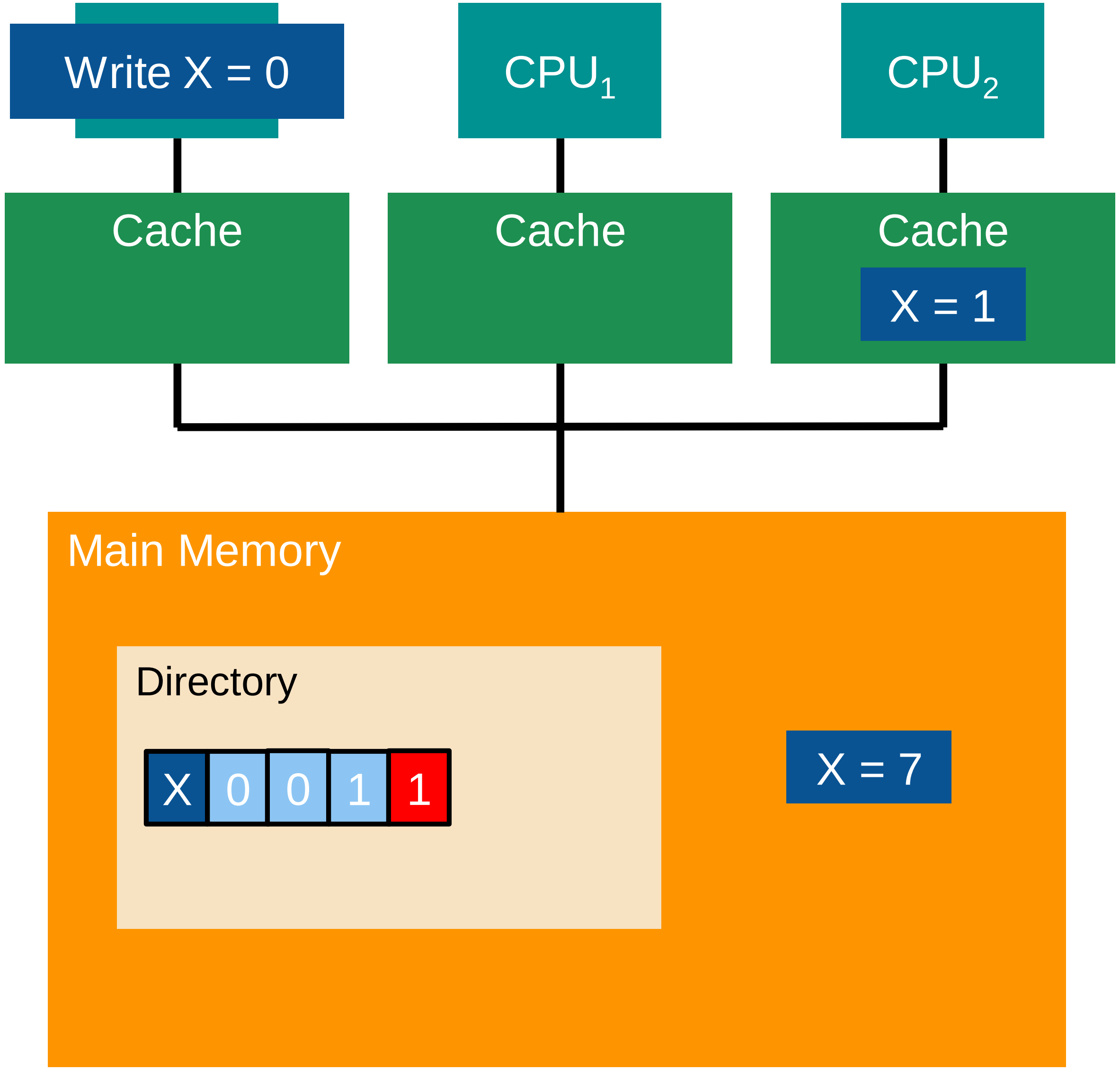
Directory-based CC: Write miss

- P_0 intends to write, misses



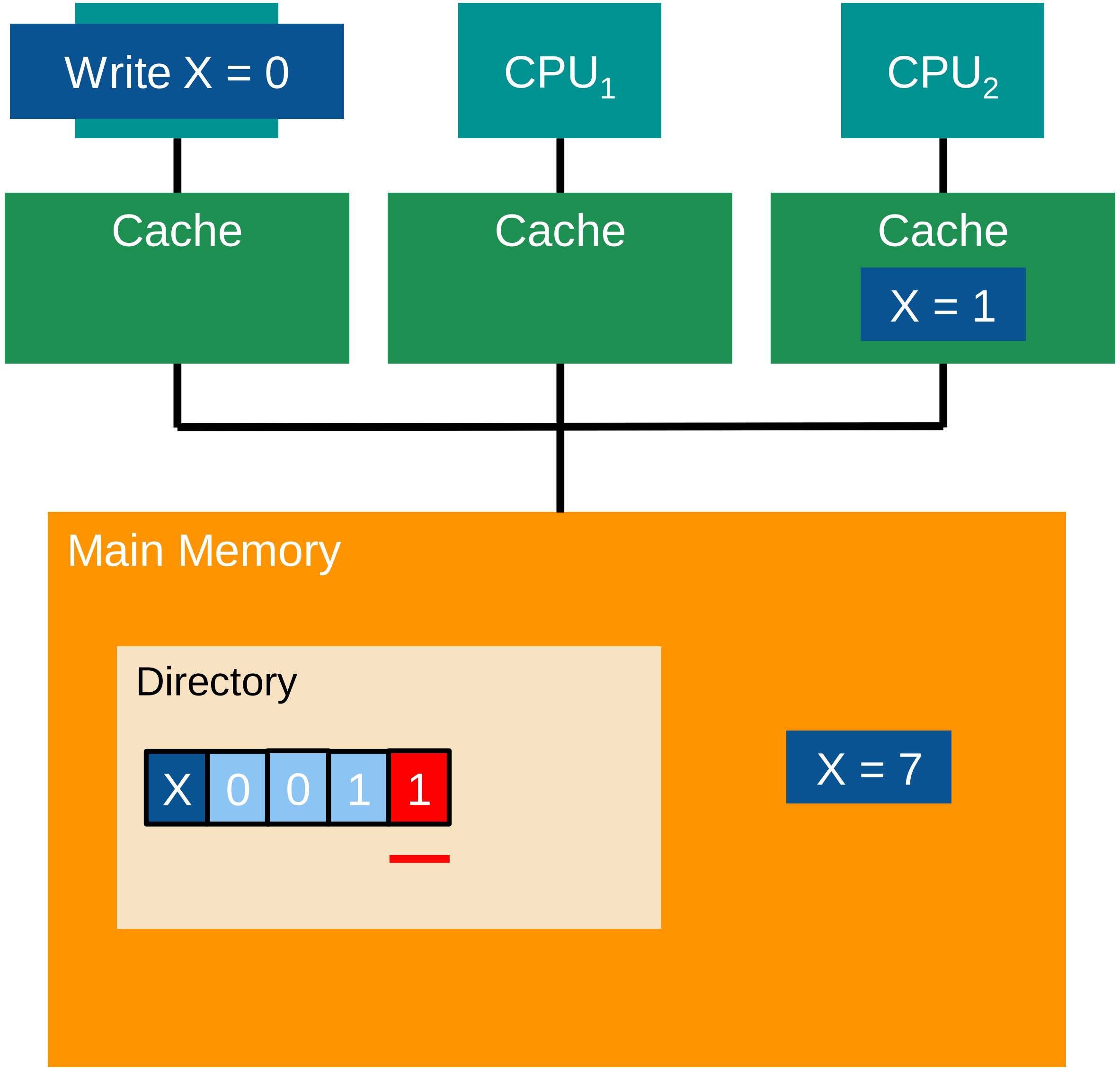
Directory-based CC: Write miss

- P_0 intends to write, misses



Directory-based CC: Write miss

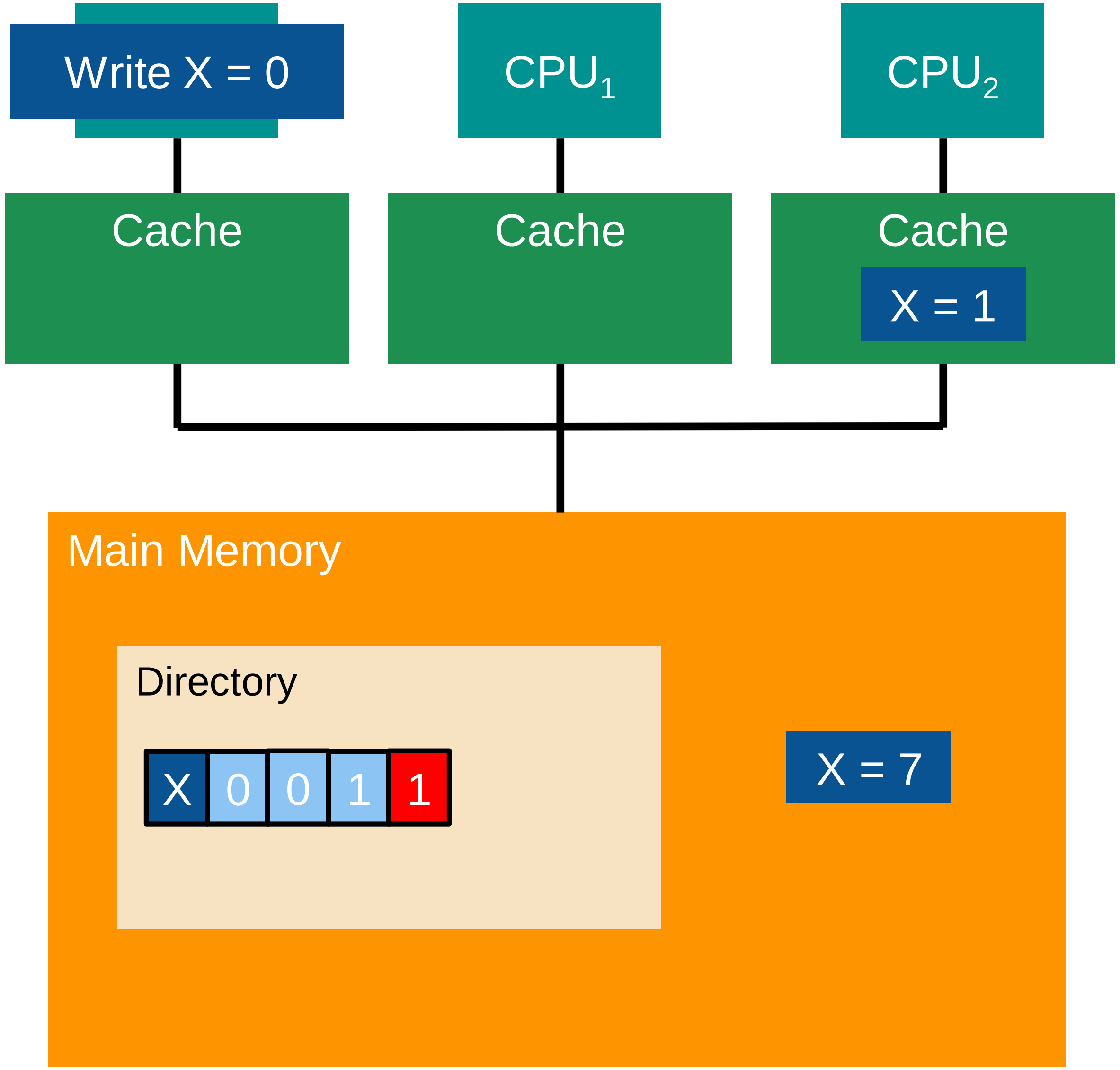
- P_0 intends to write, misses
- If dirty bit is on



X	0	0	1	1

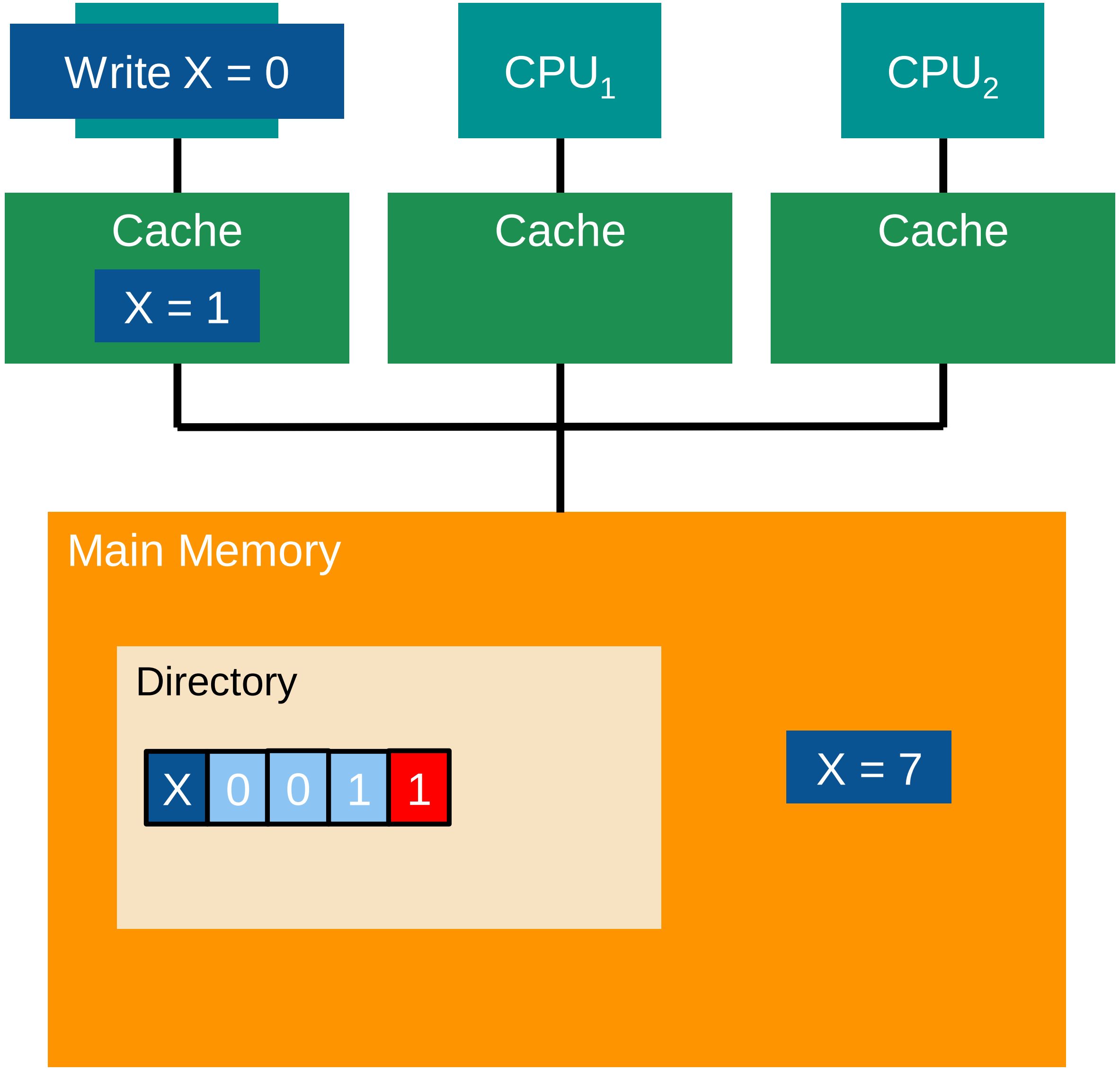
Directory-based CC: Write miss

- **P_0 intends to write, misses**
- **If dirty bit is on**
  - Recall cache line from owner P_j



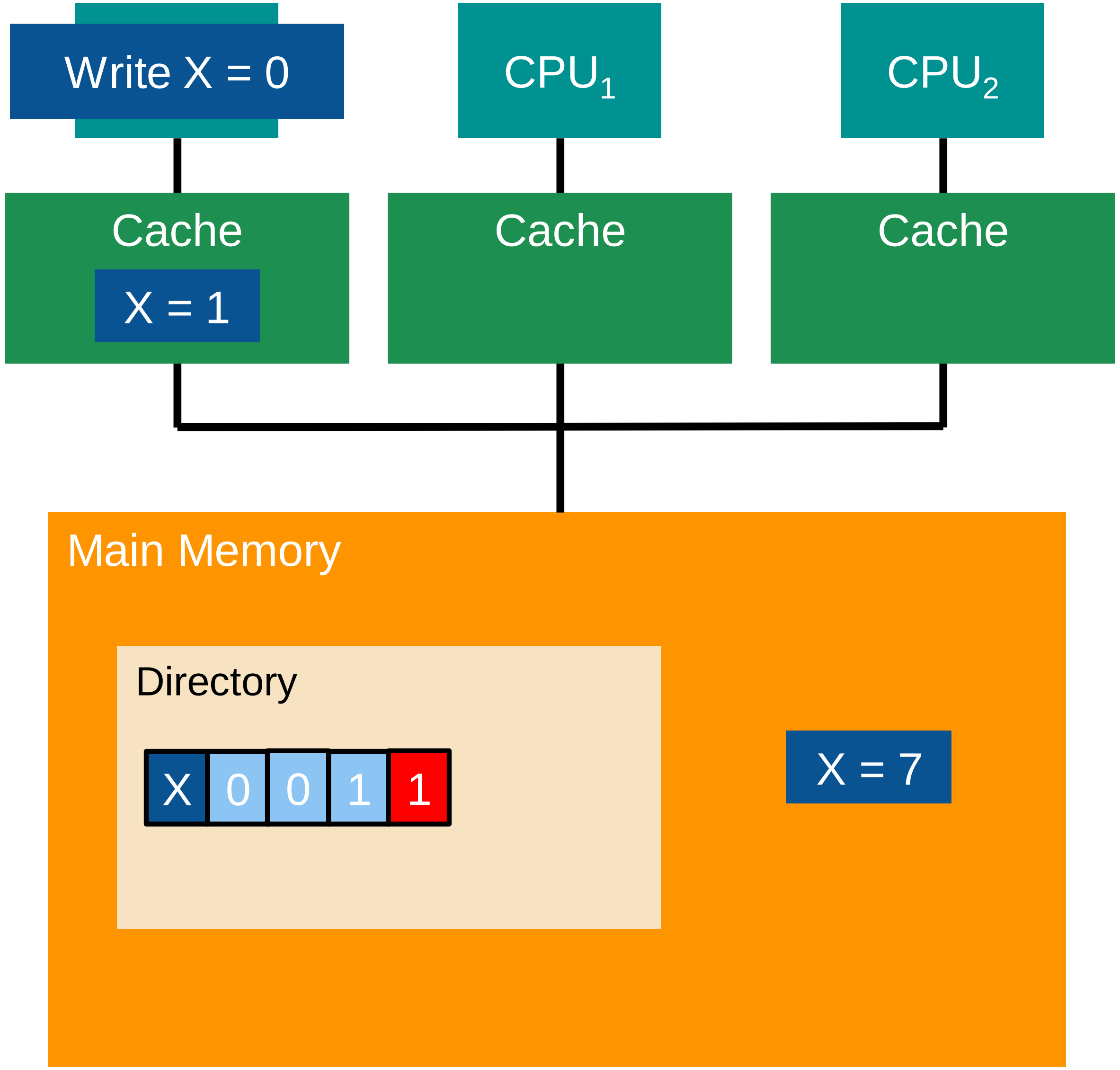
Directory-based CC: Write miss

- **P_0 intends to write, misses**
- **If dirty bit is on**
  - Recall cache line from owner P_j



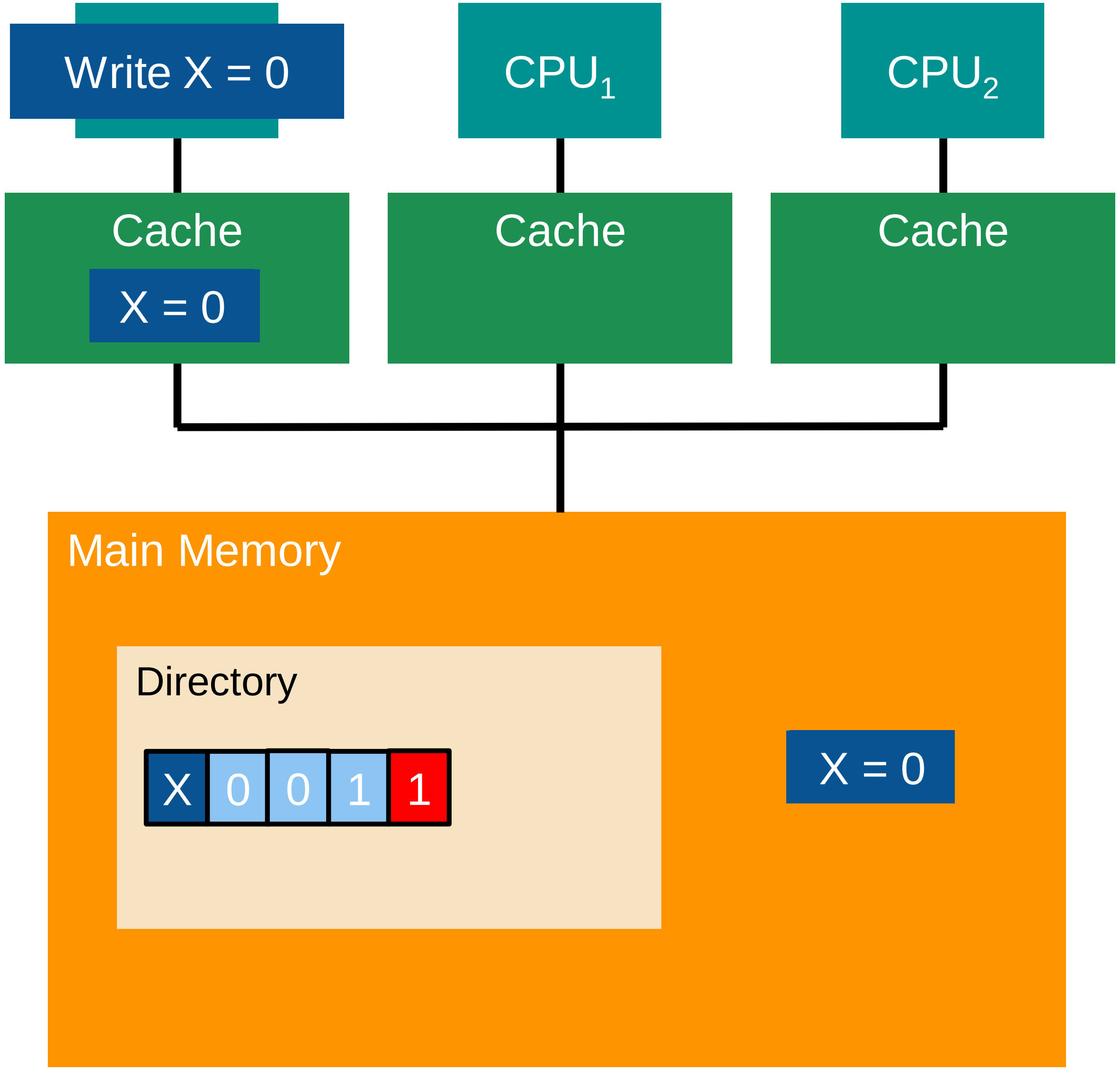
Directory-based CC: Write miss

- **P_0 intends to write, misses**
- **If dirty bit is on**
  - Recall cache line from owner P_j
  - Update memory



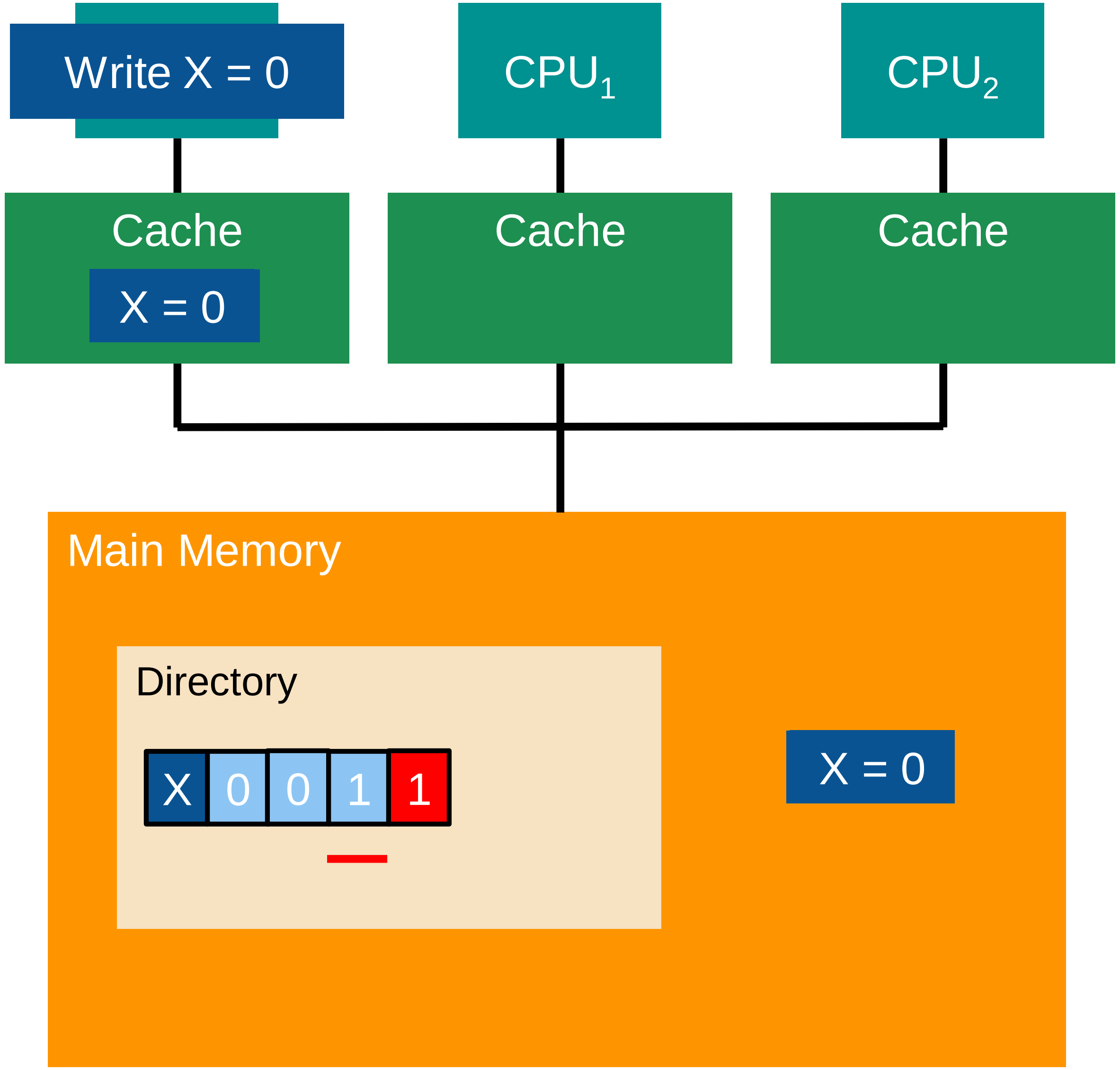
Directory-based CC: Write miss

- P_0 intends to write, misses
- If dirty bit is on
  - Recall cache line from owner P_j
  - Update memory



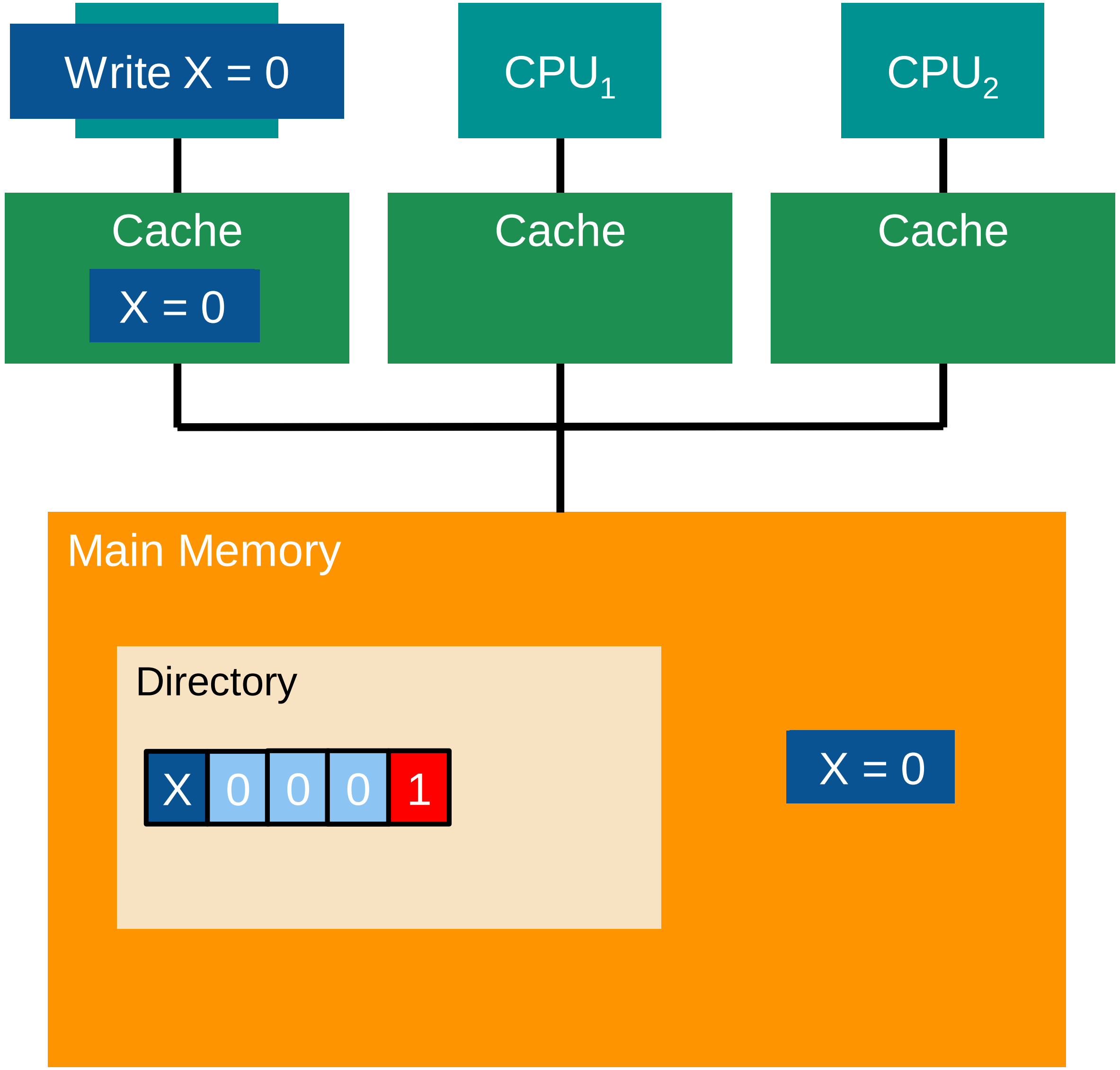
Directory-based CC: Write miss

- **P_0 intends to write, misses**
- **If dirty bit is on**
  - Recall cache line from owner P_j
  - Update memory
  - Unset presence[j]



Directory-based CC: Write miss

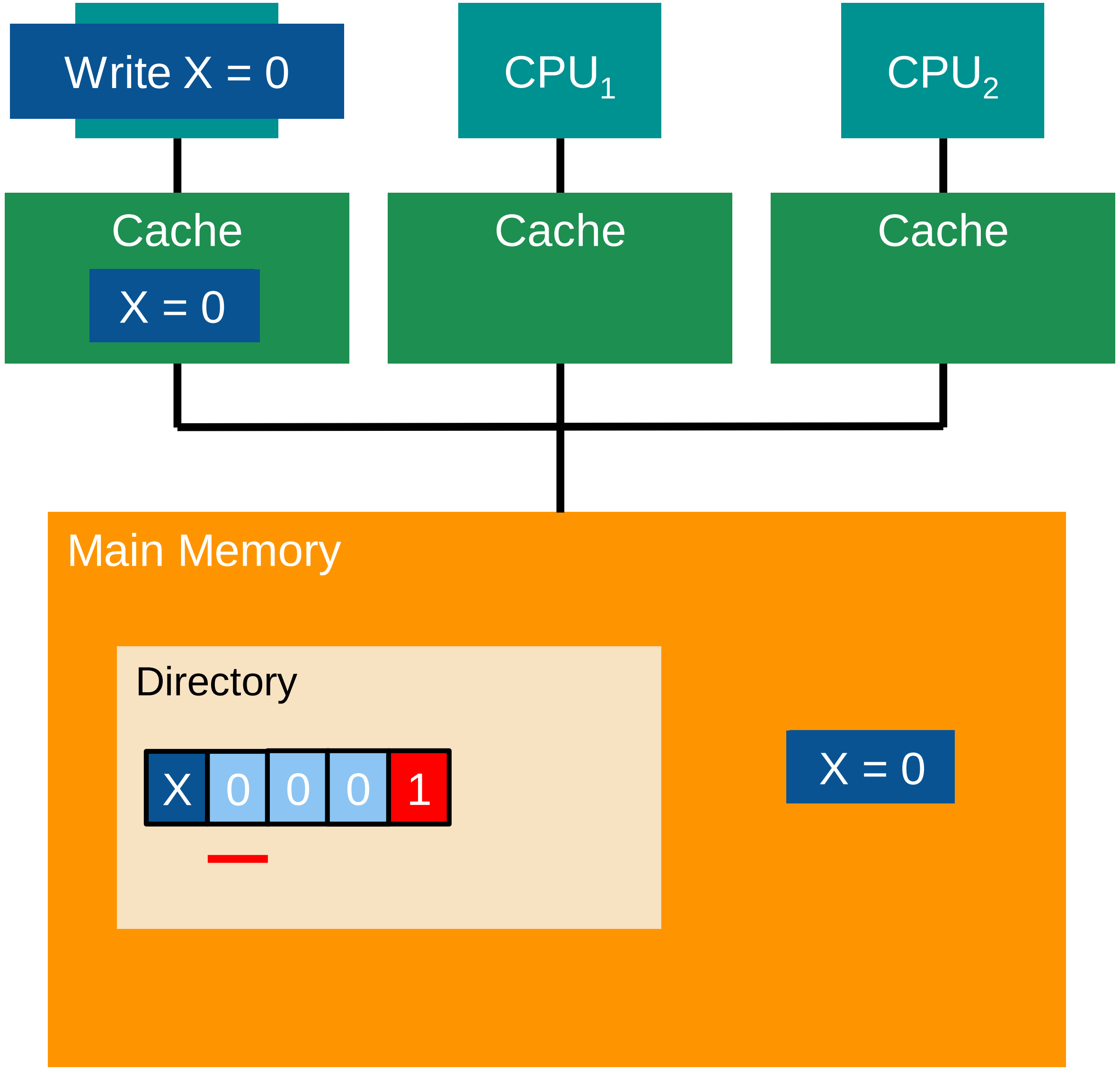
- **P_0 intends to write, misses**
- **If dirty bit is on**
  - Recall cache line from owner P_j
  - Update memory
  - Unset presence[j]



Directory-based CC: Write miss

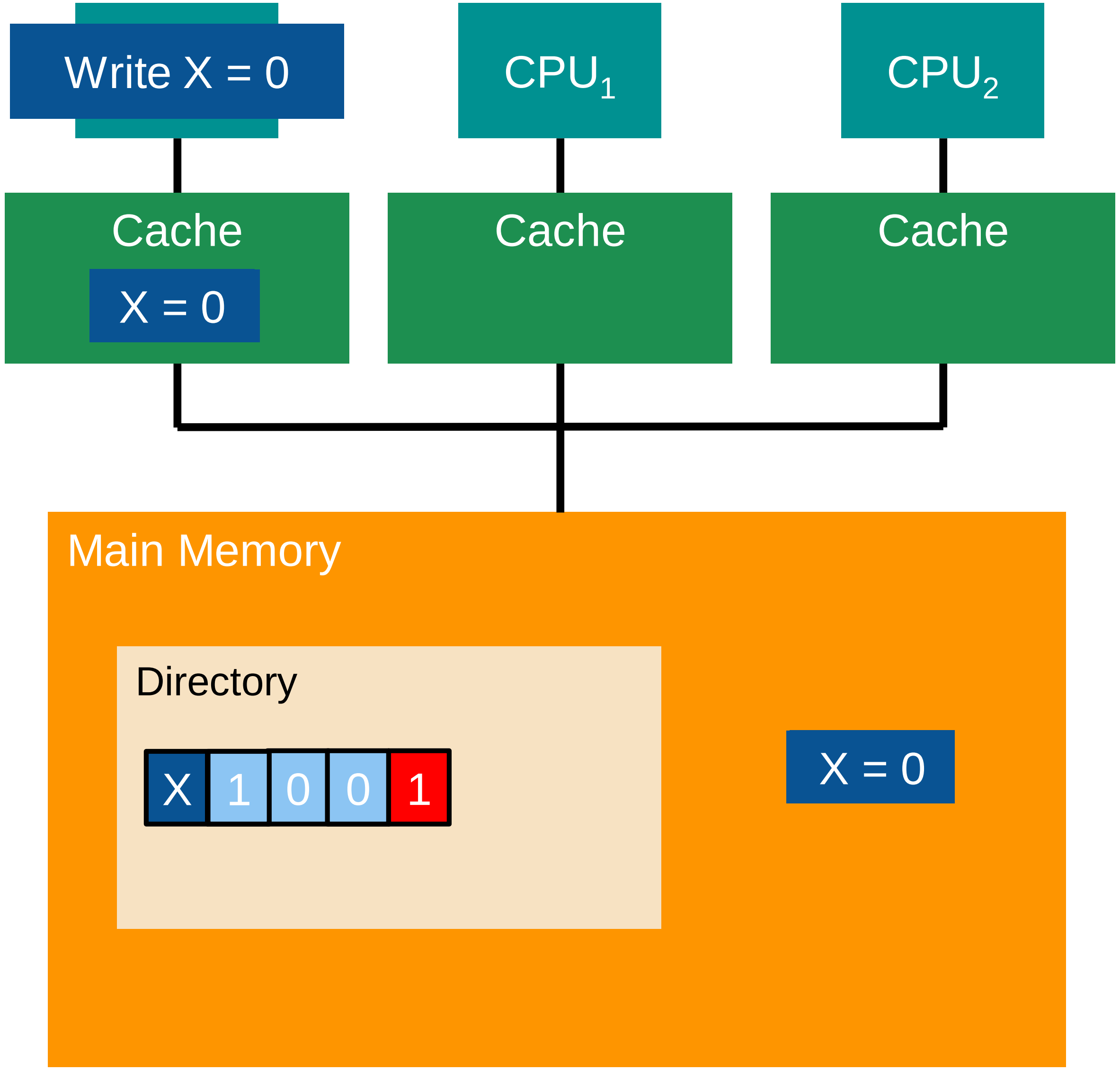
- **P_0 intends to write, misses**

- **If dirty bit is on**
  - Recall cache line from owner P_j
  - Update memory
  - Unset presence[j]
  - Set presence[i], dirty bit remains set



Directory-based CC: Write miss

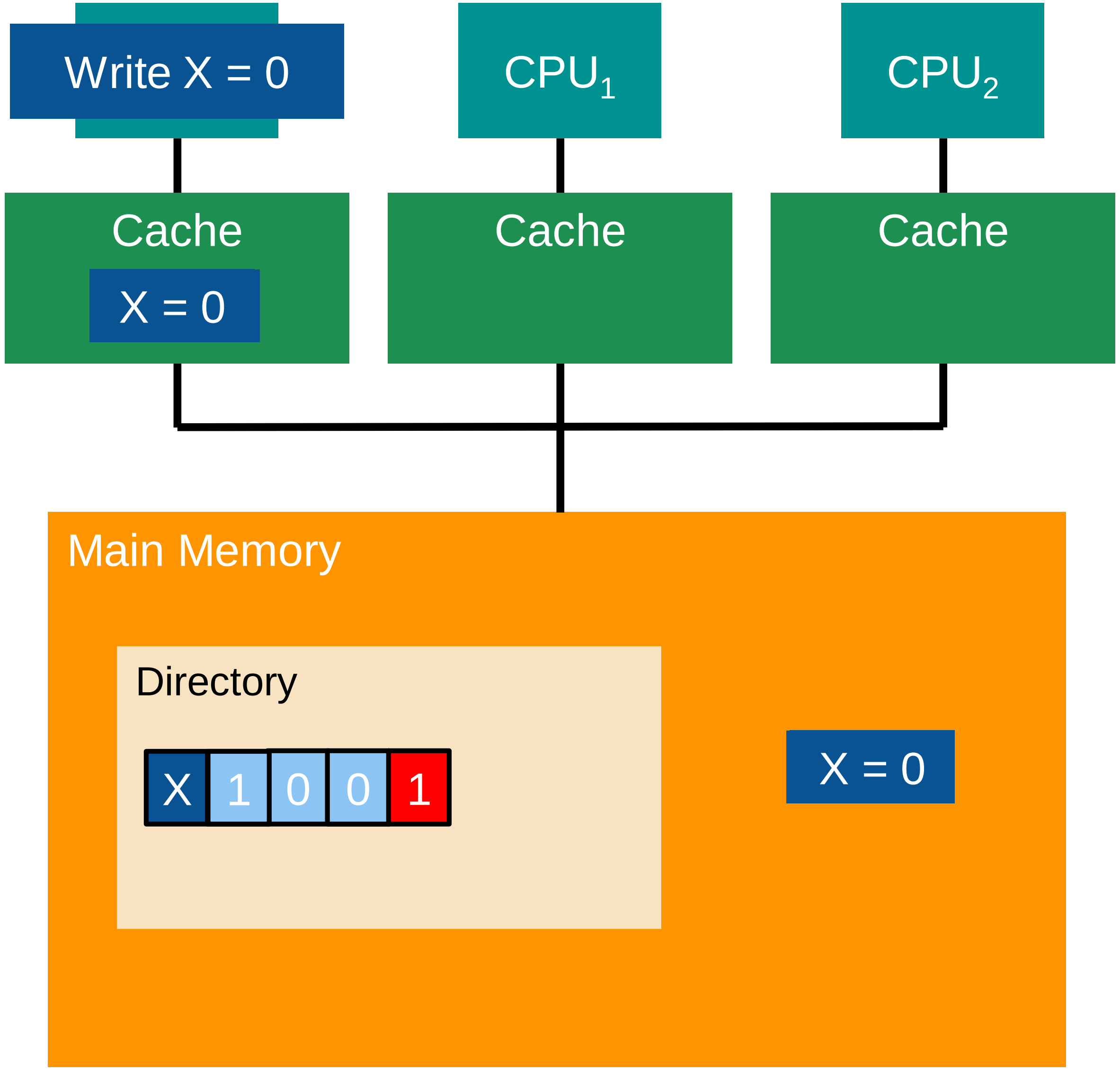
- **P_0 intends to write, misses**
- **If dirty bit is on**
  - Recall cache line from owner P_j
  - Update memory
  - Unset presence[j]
  - Set presence[i], dirty bit remains set



Directory-based CC: Write miss

- **P_0 intends to write, misses**

- **If dirty bit is on**
  - Recall cache line from owner P_j
  - Update memory
  - Unset presence[j]
  - Set presence[i], dirty bit remains set
  - Acknowledge to writer



Discussion

- **Scaling of memory bandwidth**
  - No centralized memory

- **Directory-based approaches scale with restrictions**
  - Require presence bit for each cache
  - Number of bits determined at design time
  - Directory requires memory (size scales linearly)
  - Shared vs. distributed directory

- **Software-emulation**
  - Distributed shared memory (DSM)
  - Emulate cache coherence in software (e.g., TreadMarks)
  - Often on a per-page basis, utilizes memory virtualization and paging

Open Problems (for projects, theses, research)

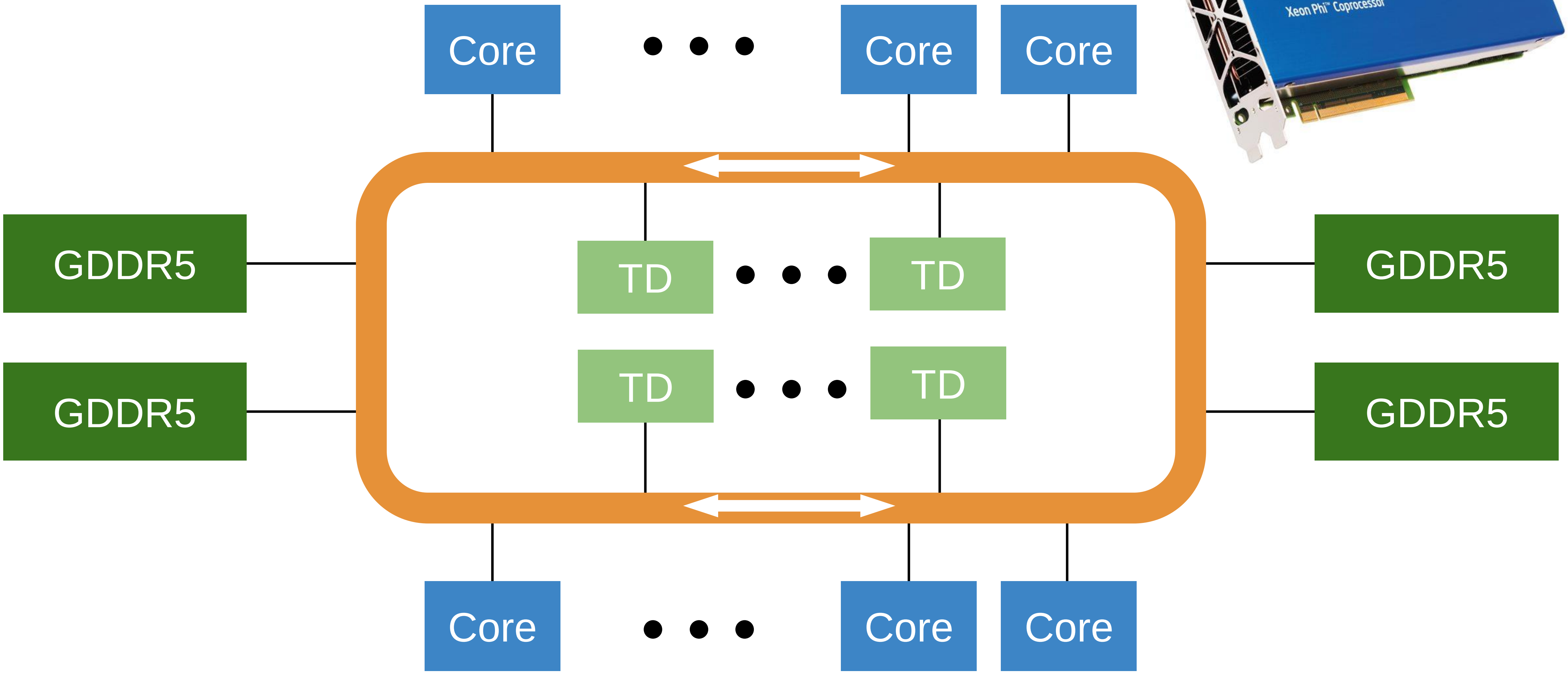
- **Tune algorithms to cache-coherence schemes**
  - What is the optimal parallel algorithm for a given scheme?
  - Parameterize for an architecture

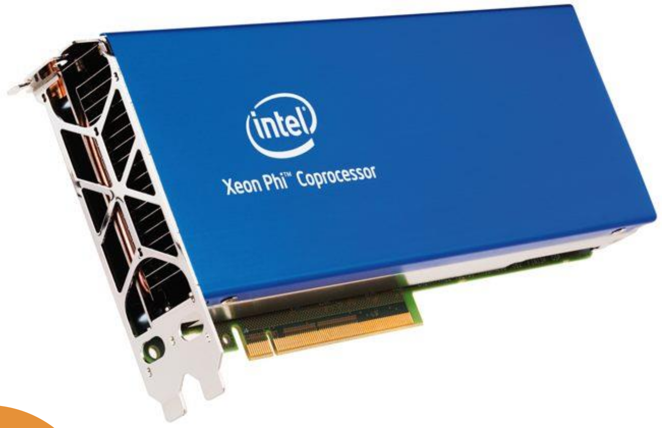
- **Measure and classify hardware**
  - Read Maranget et al. “A Tutorial Introduction to the ARM and POWER Relaxed Memory Models” and have fun!
  - RDMA consistency is barely understood!
  - GPU memories are not well understood!

  Huge potential for new insights!

- **Can we program (easily) without cache coherence?**
  - How to fix the problems with inconsistent values?
  - Compiler support (issues with arrays)?

Case Study: Intel Xeon Phi

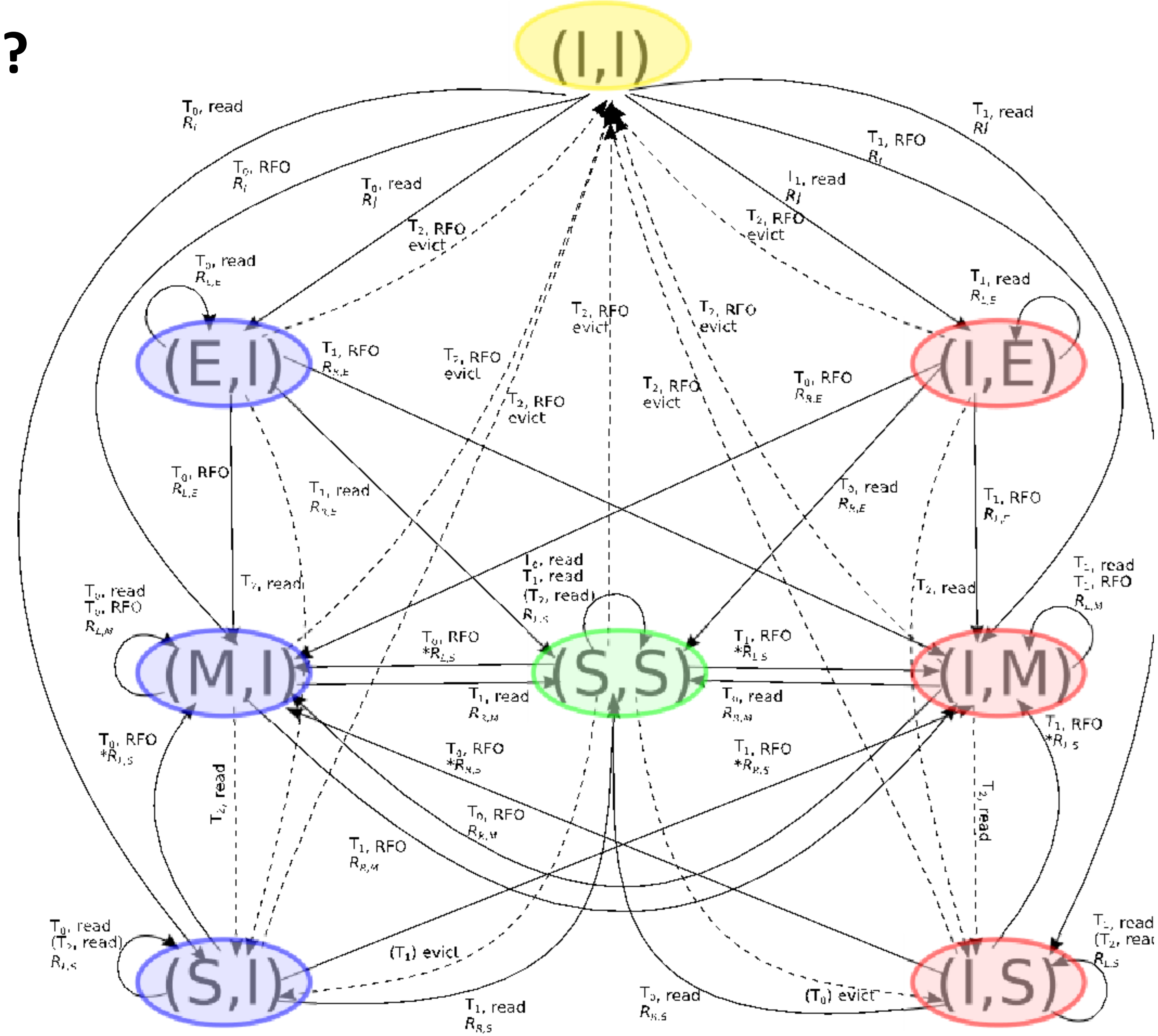




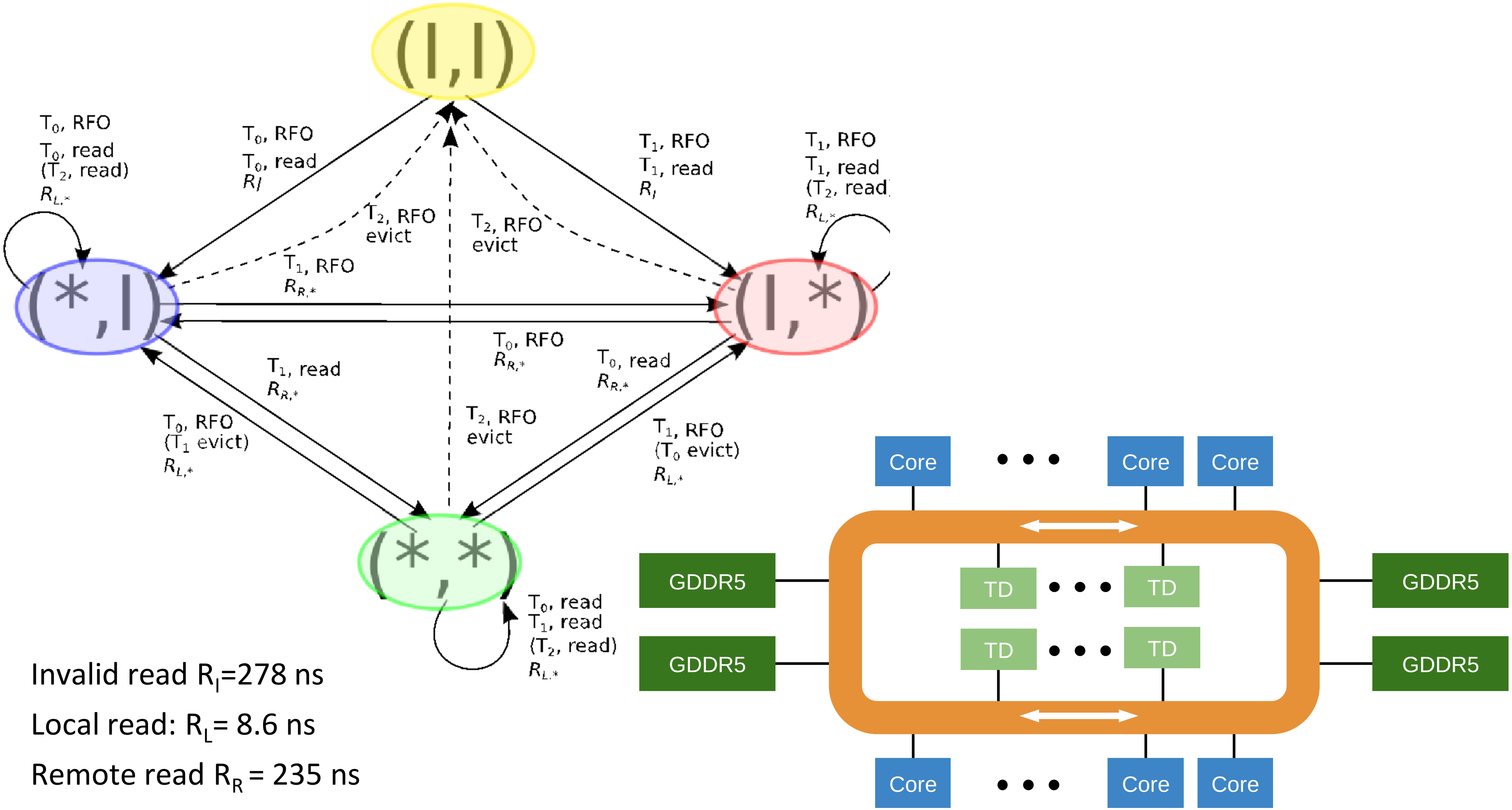
Communication?

Ramos, Hoefler: "Modeling Communication in Cache-Coherent SMP Systems - A Case-Study with Xeon Phi ", HPDC'13

Communication?



Ramos, Hoefler: “Modeling Communication in Cache-Coherent SMP Systems - A Case-Study with Xeon Phi “, HPDC’13



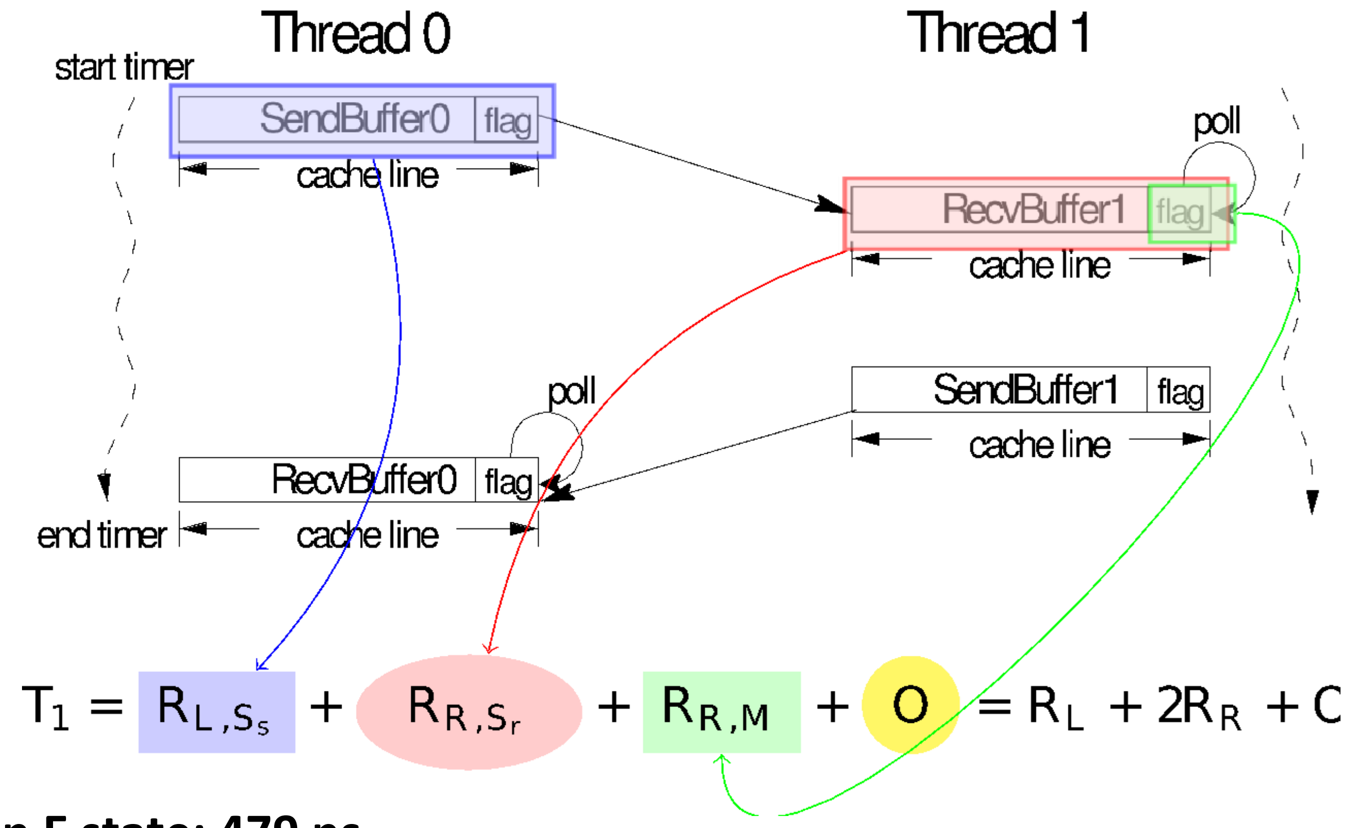
Invalid read R_I=278 ns

Local read: R_L= 8.6 ns

Remote read R_R = 235 ns

Inspired by Molka et al.: “Memory performance and cache coherency effects on an Intel Nehalem multiprocessor system”

Single-Line Ping Pong



$$T_1 = R_{L,S_s} + R_{R,S_r} + R_{R,M} + O = R_L + 2R_R + C$$

- **Prediction for both in E state: 479 ns**
  - Measurement: 497 ns (O=18)

Ramos, Hoefler: “Modeling Communication in Cache-Coherent SMP Systems - A Case-Study with Xeon Phi “, HPDC’13

Multi-Line Ping Pong

- **More complex due to prefetch**

Number of CLs

Amortization of startup

$$\mathcal{T}_N = o \cdot N + q - \frac{p}{N}$$

Asymptotic Fetch Latency for each cache line (optimal prefetch!)

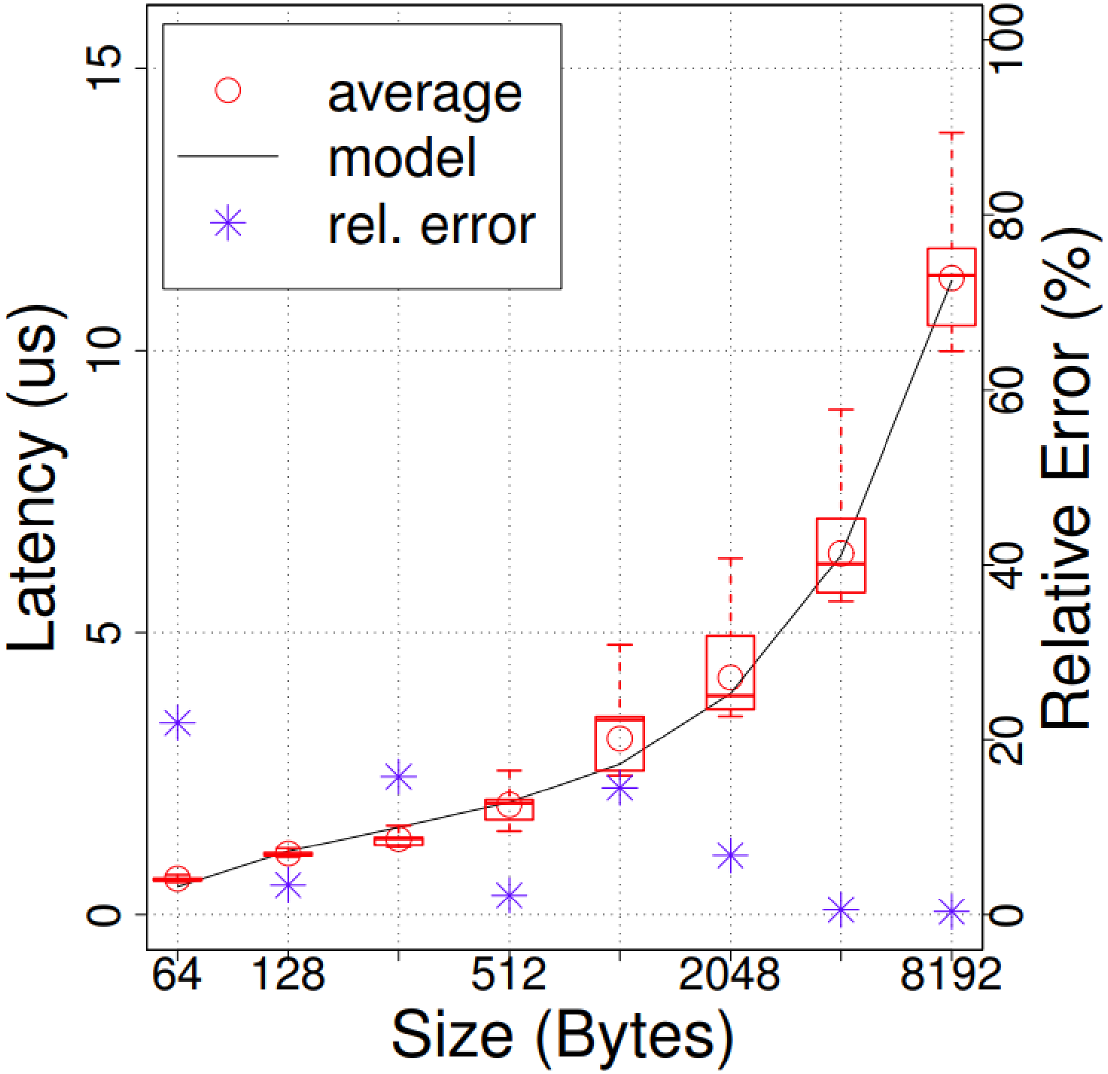
Startup overhead

Ramos, Hoefler: "Modeling Communication in Cache-Coherent SMP Systems - A Case-Study with Xeon Phi ", HPDC'13

Multi-Line Ping Pong

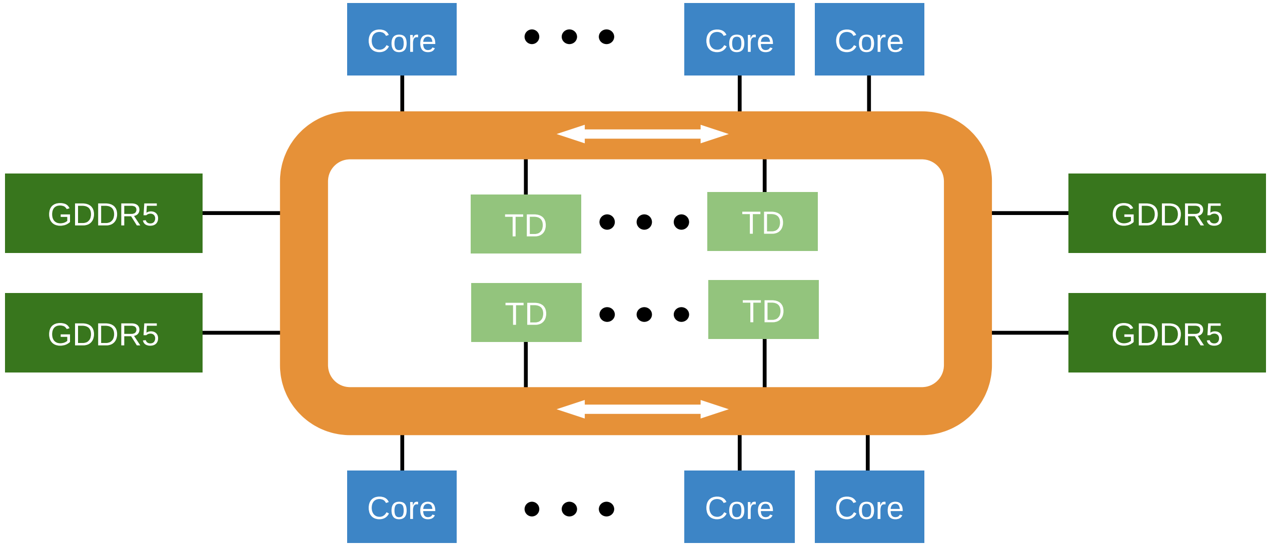
$$\mathcal{T}_N = o \cdot N + q - \frac{p}{N}$$

- **E state:**
  - o=76 ns
  - q=1,521ns
  - p=1,096ns
- **I state:**
  - o=95ns
  - q=2,750ns
  - p=2,017ns



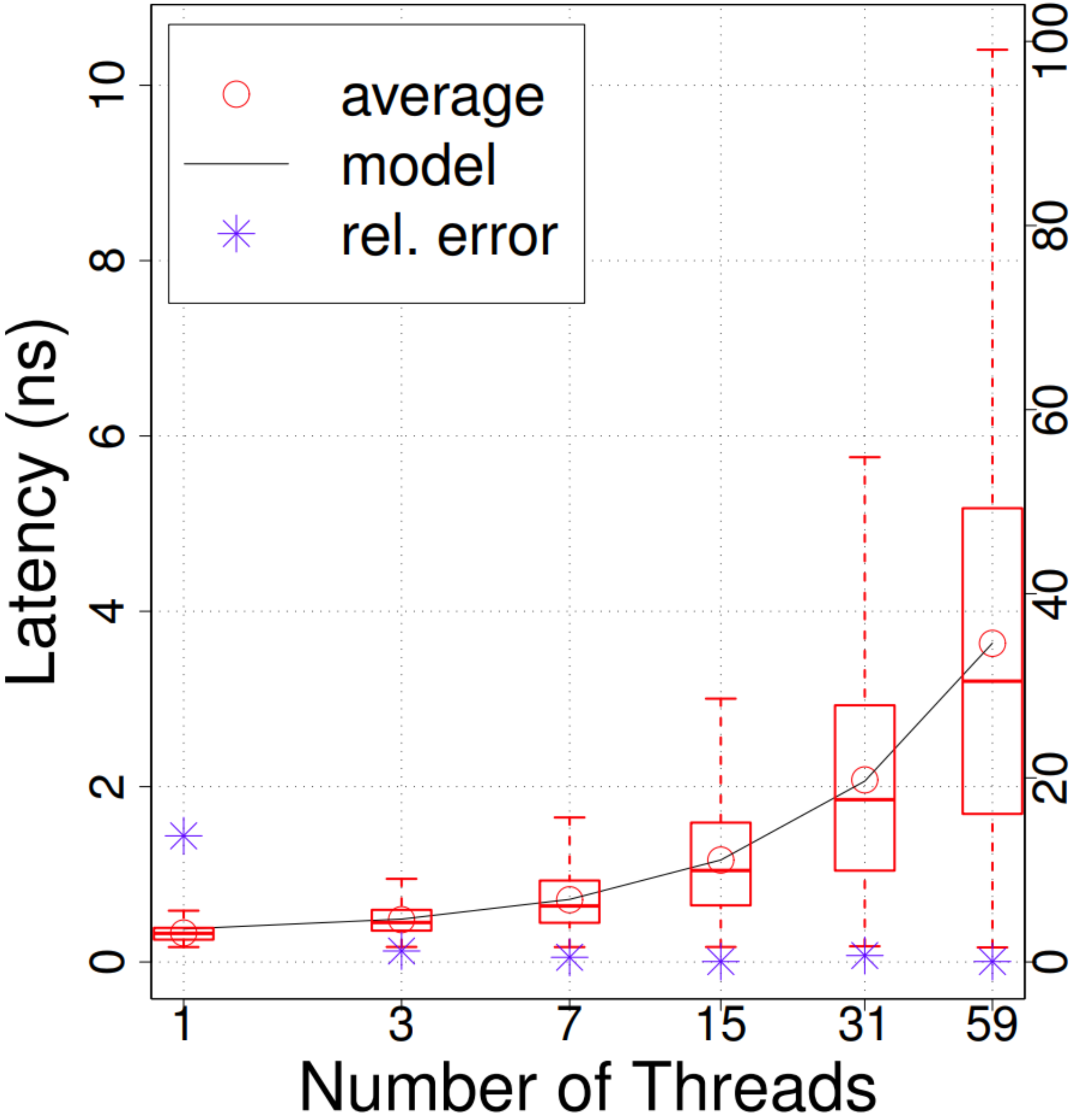
Ramos, Hoefler: “Modeling Communication in Cache-Coherent SMP Systems - A Case-Study with Xeon Phi “, HPDC’13

DTD Contention ☹



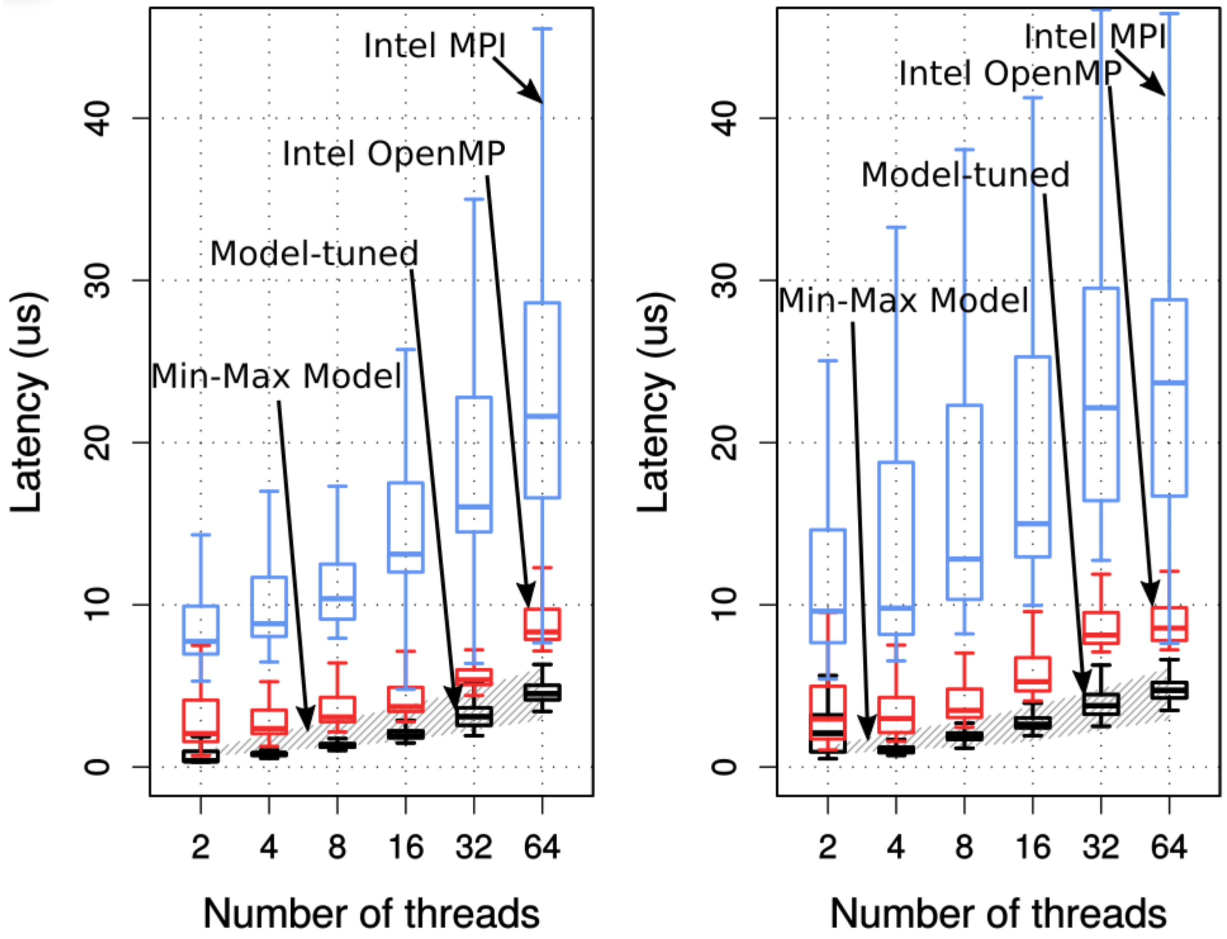
- **E state:**
  - a=0ns
  - b=320ns
  - c=56.2ns

$$\mathcal{T}_C(n_{th}) = c \cdot n_{th} + b - \frac{a}{n_{th}}$$



Ramos, Hoefler: *"Modeling Communication in Cache-Coherent SMP Systems - A Case-Study with Xeon Phi ", HPDC'13*

Optimizations against vendor libraries

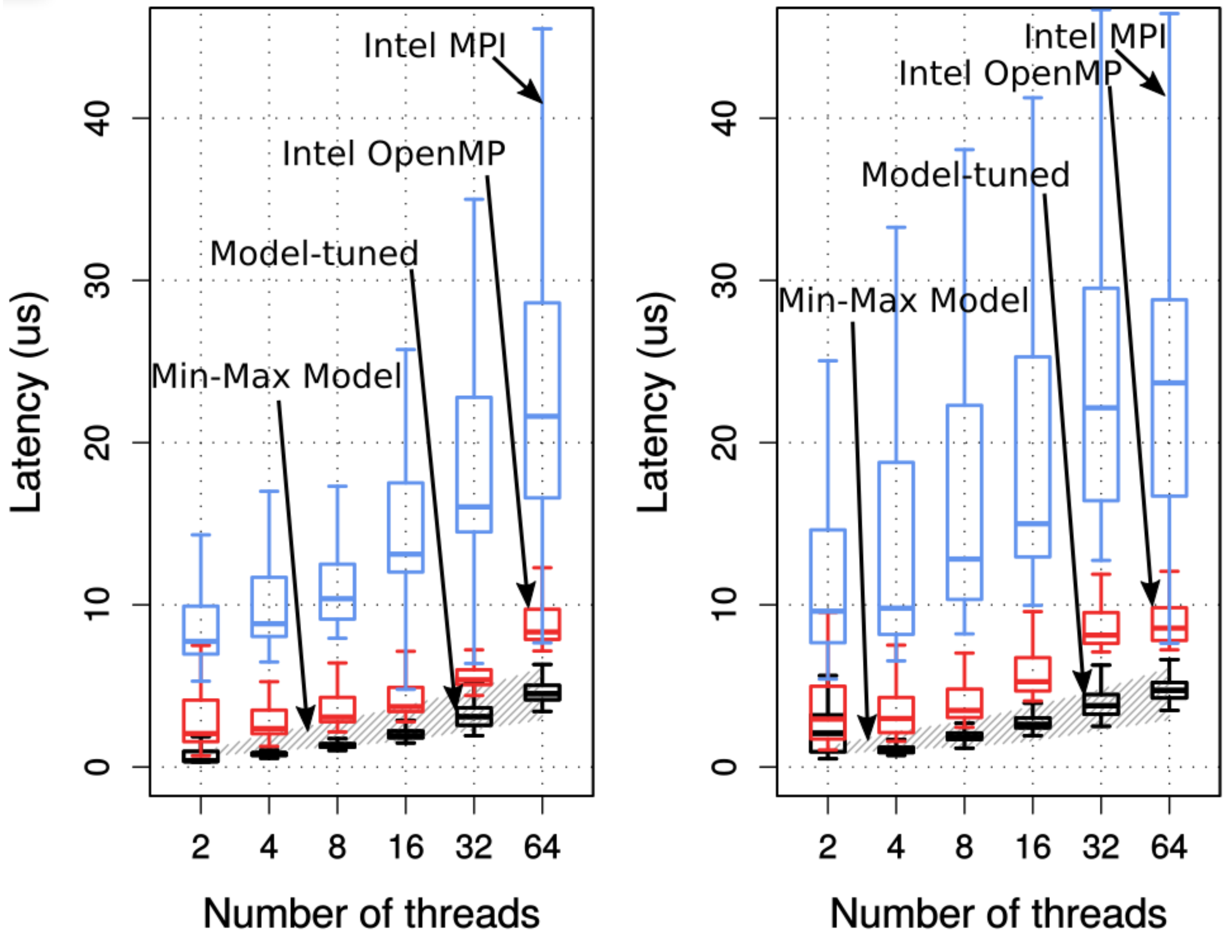


(a) Filling Tiles. (b) Scatter.

Barrier (7x faster than OpenMP)

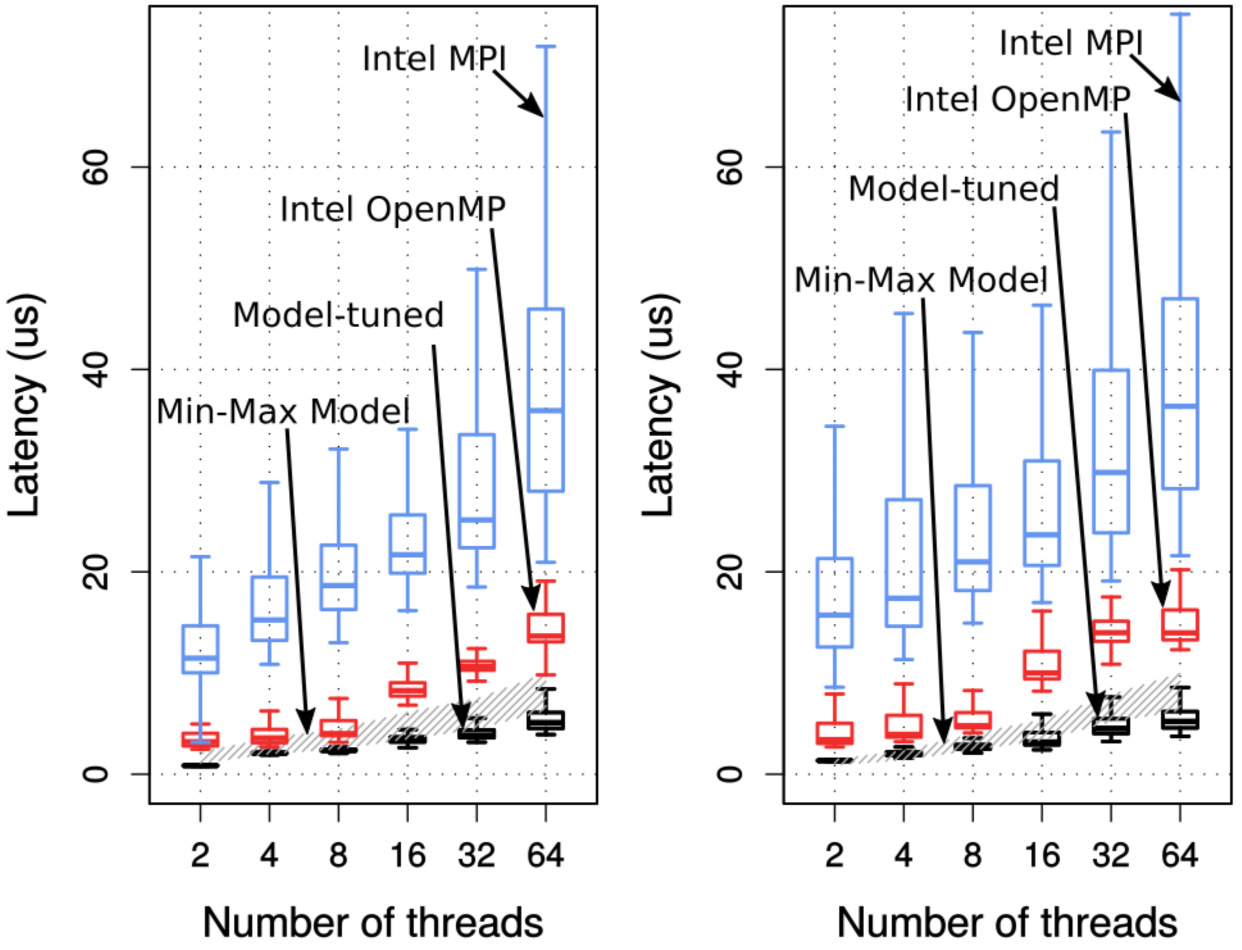
Ramos, Hoefler: "Capability Models for Manycore Memory Systems: A Case-Study with Xeon Phi KNL", IPDPS'17 (video: https://www.youtube.com/watch?v=10Mo3MnWR74)

Optimizations against vendor libraries



(a) Filling Tiles.

(b) Scatter.



(a) Filling Tiles.

(b) Scatter.

Barrier (7x faster than OpenMP)

Reduce (5x faster then OpenMP)

Ramos, Hoefler: "Capability Models for Manycore Memory Systems: A Case-Study with Xeon Phi KNL", IPDPS'17 (video: https://www.youtube.com/watch?v=10Mo3MnWR74)

Image credits

- **Slide 23, die map:** https://superuser.com/questions/386745/how-to-make-caches-with-equal-bitline-and-wordline-lengths
- **Slide 23, RAM: © Raimond Spekking / CC BY-SA 4.0 (via Wikimedia Commons)** https://commons.wikimedia.org/wiki/File:Apacer_SDRAM-3386.jpg