Design of Digital Circuits

Lecture 25a: More Caches

Prof. Onur Mutlu
ETH Zurich

Spring 2018

31 May 2018

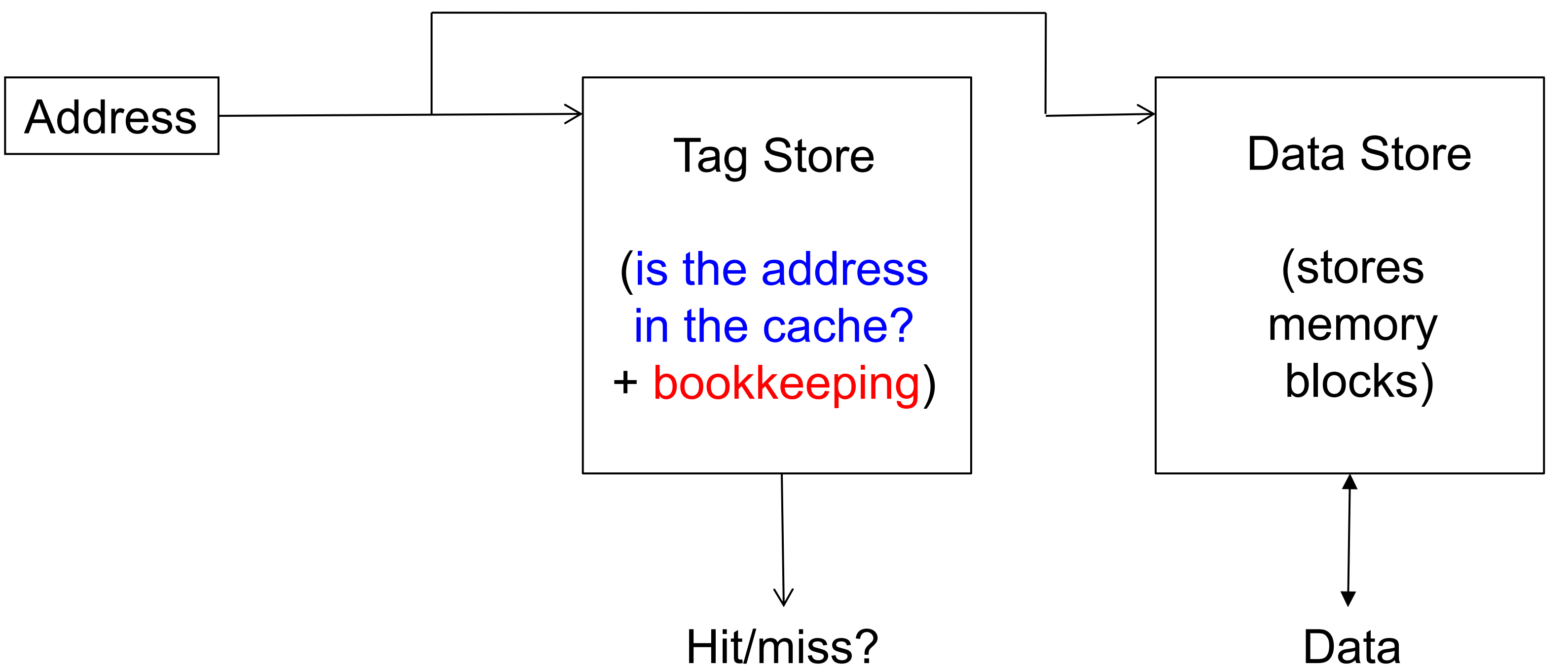
Readings

- Caches

- Required
  - H&H Chapters 8.1-8.3
  - Refresh: P&P Chapter 3.5

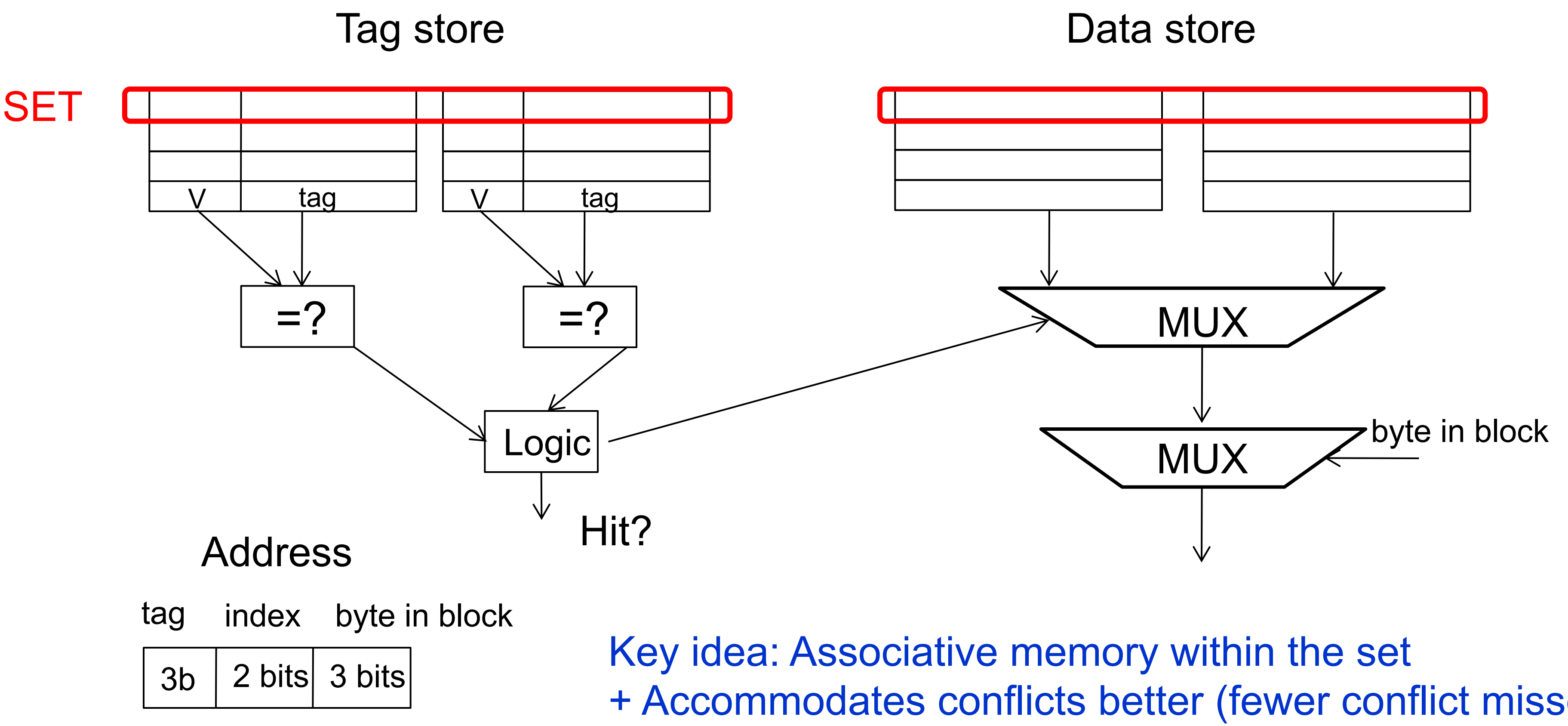
- Recommended
  - An early cache paper by Maurice Wilkes
    - Wilkes, "Slave Memories and Dynamic Storage Allocation," IEEE Trans. On Electronic Computers, 1965.

Recall: Cache Structure



Recall: Set Associativity

- Addresses 0 and 8 always conflict in direct mapped cache
- Instead of having one column of 8, have 2 columns of 4 blocks



Key idea: Associative memory within the set
+ Accommodates conflicts better (fewer conflict misses)
-- More complex, slower access, larger tag store

What's In A Tag Store Entry?

- Valid bit
- Tag
- Replacement policy bits

- Dirty bit?
  - Write back vs. write through caches

Handling Writes (I)

- When do we write the modified data in a cache to the next level?
  - Write through: At the time the write happens
  - Write back: When the block is evicted

- Write-back
  + Can combine multiple writes to the same block before eviction
    - Potentially saves bandwidth between cache levels + saves energy

  -- Need a bit in the tag store indicating the block is "dirty/modified"

- Write-through
  + Simpler
  + All levels are up to date. Consistency: Simpler cache coherence because no need to check close-to-processor caches' tag stores for presence

  -- More bandwidth intensive; no combining of writes

Handling Writes (II)

- Do we allocate a cache block on a write miss?
  - Allocate on write miss: Yes
  - No-allocate on write miss: No

- Allocate on write miss

  + Can combine writes instead of writing each of them individually to next level

  + Simpler because write misses can be treated the same way as read misses

  -- Requires transfer of the whole cache block

- No-allocate

  + Conserves cache space if locality of writes is low (potentially better cache hit rate)

Handling Writes (III)

- What if the processor writes to an entire block over a small amount of time?

- Is there any need to bring the block into the cache from memory in the first place?

- Why do we not simply write to only a *portion* of the block, i.e., subblock
  - E.g., 4 bytes out of 64 bytes
  - Problem: Valid and dirty bits are associated with the entire 64 bytes, not with each individual 4 bytes

Subblocked (Sectored) Caches

- Idea: Divide a block into subblocks (or sectors)
  - Have separate valid and dirty bits for each subblock (sector)
  - Allocate only a subblock (or a subset of subblocks) on a request

++ No need to transfer the entire cache block into the cache

(A write simply validates and updates a subblock)

++ More freedom in transferring subblocks into the cache (a cache block does not need to be in the cache fully)

(How many subblocks do you transfer on a read?)

-- More complex design

-- May not exploit spatial locality fully

v	d	subblock	v	d	subblock	• • • •	v	d	subblock	tag

Instruction vs. Data Caches

- Separate or Unified?

- Pros and Cons of Unified:

  \+ Dynamic sharing of cache space: no overprovisioning that might happen with static partitioning (i.e., separate I and D caches)

  -- Instructions and data can thrash each other (i.e., no guaranteed space for either)

  -- I and D are accessed in different places in the pipeline. Where do we place the unified cache for fast access?

- First level caches are almost always split
  - Mainly for the last reason above
- Higher level caches are almost always unified

Multi-level Caching in a Pipelined Design

- First-level caches (instruction and data)
  - Decisions very much affected by cycle time
  - Small, lower associativity; latency is critical
  - Tag store and data store accessed in parallel
- Second-level caches
  - Decisions need to balance hit rate and access latency
  - Usually large and highly associative; latency not as important
  - Tag store and data store accessed serially

- Serial vs. Parallel access of levels
  - Serial: Second level cache accessed only if first-level misses
  - Second level does not see the same accesses as the first
    - First level acts as a filter (filters some temporal and spatial locality)
    - Management policies are therefore different

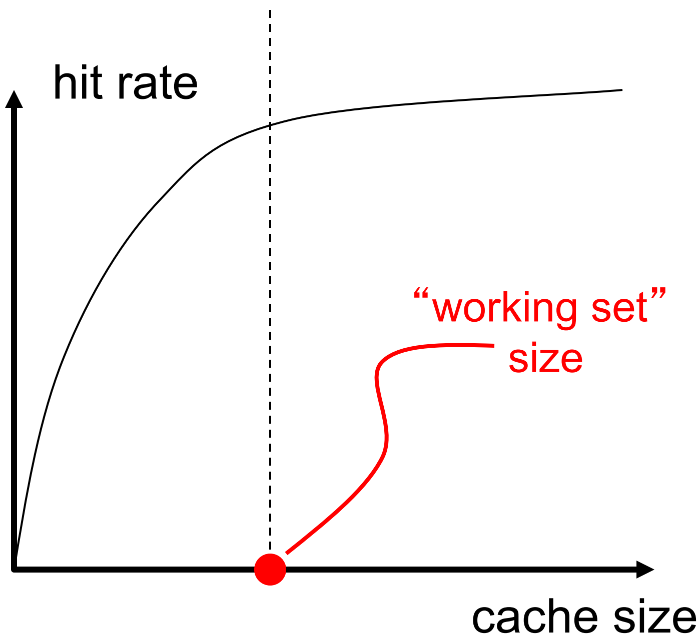
Cache Performance

Cache Parameters vs. Miss/Hit Rate

- Cache size
- Block size
- Associativity
- Replacement policy
- Insertion/Placement policy

Cache Size

- Cache size: total data (not including tag) capacity
  - bigger can exploit temporal locality better
  - not ALWAYS better
- Too large a cache adversely affects hit and miss latency
  - smaller is faster => bigger is slower
  - access time may degrade critical path
- Too small a cache
  - doesn't exploit temporal locality well
  - useful data replaced often
- Working set: the whole set of data the executing application references
  - Within a time interval

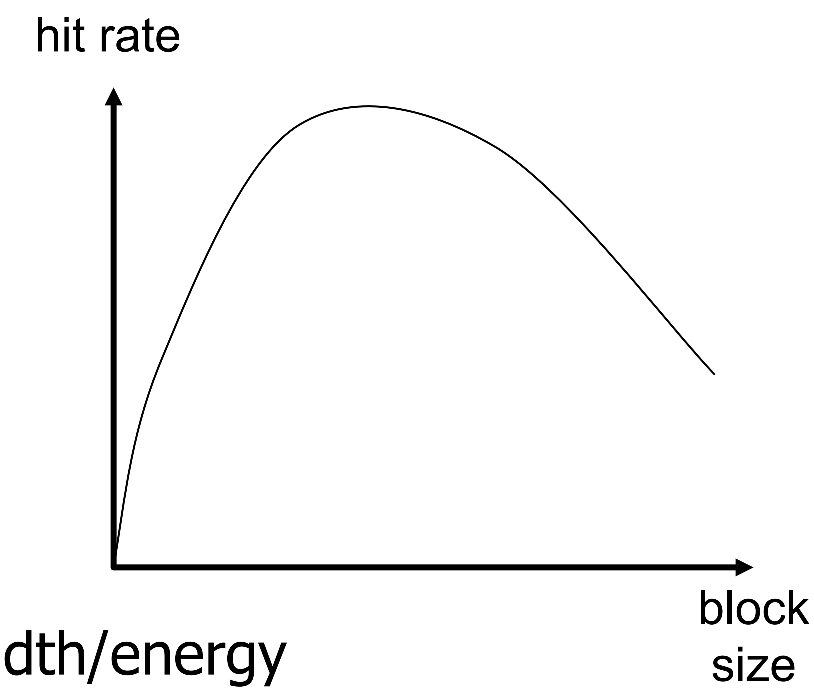


Block Size

- Block size is the data that is associated with an address tag
  - not necessarily the unit of transfer between hierarchies
    - Sub-blocking: A block divided into multiple pieces (each w/ V/D bits)

- Too small blocks
  - don't exploit spatial locality well
  - have larger tag overhead

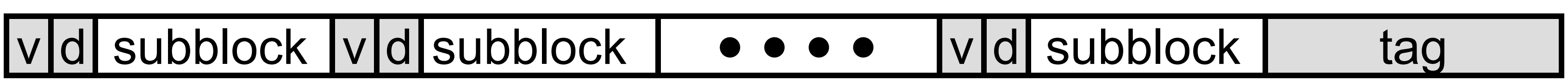
- Too large blocks
  - too few total # of blocks → less temporal locality exploitation
  - waste of cache space and bandwidth/energy if spatial locality is not high



Large Blocks: Critical-Word and Subblocking

- Large cache blocks can take a long time to fill into the cache
  - fill cache line critical word first
  - restart cache access before complete fill

- Large cache blocks can waste bus bandwidth
  - divide a block into subblocks
  - associate separate valid and dirty bits for each subblock
  - Recall: When is this useful?

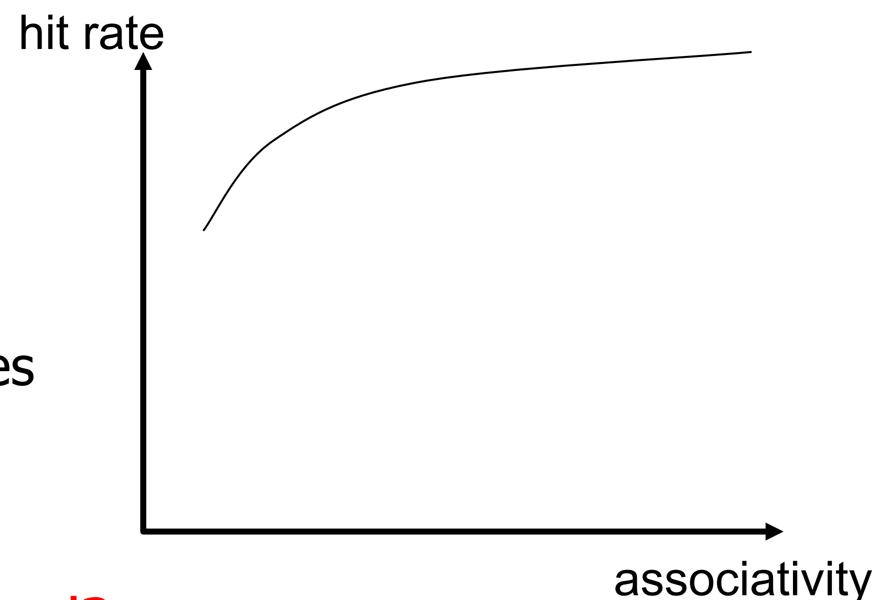


Associativity

- How many blocks can be present in the same index (i.e., set)?

- Larger associativity
  - lower miss rate (reduced conflicts)
  - higher hit latency and area cost (plus diminishing returns)

- Smaller associativity
  - lower cost
  - lower hit latency
    - Especially important for L1 caches



- Is power of 2 associativity required?

Classification of Cache Misses

- Compulsory miss
  - first reference to an address (block) always results in a miss
  - subsequent references should hit unless the cache block is displaced for the reasons below

- Capacity miss
  - cache is too small to hold everything needed
  - defined as the misses that would occur even in a fully-associative cache (with optimal replacement) of the same capacity

- Conflict miss
  - defined as any miss that is neither a compulsory nor a capacity miss

How to Reduce Each Miss Type

- Compulsory
  - Caching cannot help
  - Prefetching can: Anticipate which blocks will be needed soon
- Conflict
  - More associativity
  - Other ways to get more associativity without making the cache associative
    - Victim cache
    - Better, randomized indexing
    - Software hints?
- Capacity
  - Utilize cache space better: keep blocks that will be referenced
  - Software management: divide working set and computation such that each “computation phase” fits in cache

How to Improve Cache Performance

- Three fundamental goals

- Reducing miss rate
  - Caveat: reducing miss rate can reduce performance if more costly-to-refetch blocks are evicted

- Reducing miss latency or miss cost

- Reducing hit latency or hit cost

- The above three **together** affect performance

Improving Basic Cache Performance

- Reducing miss rate
  - More associativity
  - Alternatives/enhancements to associativity
    - Victim caches, hashing, pseudo-associativity, skewed associativity
  - Better replacement/insertion policies
  - Software approaches
- Reducing miss latency/cost
  - Multi-level caches
  - Critical word first
  - Subblocking/sectoring
  - Better replacement/insertion policies
  - Non-blocking caches (multiple cache misses in parallel)
  - Multiple accesses per cycle
  - Software approaches

Software Approaches for Higher Hit Rate

- Restructuring data access patterns
- Restructuring data layout

- Loop interchange
- Data structure separation/merging
- Blocking
- …

Restructuring Data Access Patterns (I)

- Idea: Restructure data layout or data access patterns
- Example: If column-major
  - x[i+1,j] follows x[i,j] in memory
  - x[i,j+1] is far away from x[i,j]

Poor code

```
for i = 1, rows
    for j = 1, columns
        sum = sum + x[i,j]
```

Better code

```
for j = 1, columns
    for i = 1, rows
        sum = sum + x[i,j]
```

- This is called loop interchange
- Other optimizations can also increase hit rate
  - Loop fusion, array merging, …

Restructuring Data Access Patterns (II)

- Blocking
  - Divide loops operating on arrays into computation chunks so that each chunk can hold its data in the cache
  - Avoids cache conflicts between different chunks of computation
  - Essentially: Divide the working set so that each piece fits in the cache

- Also called Tiling

Restructuring Data Layout (I)

```
struct Node {
    struct Node* next;
    int key;
    char [256] name;
    char [256] school;
}

while (node) {
    if (node→key == input-key) {
        // access other fields of node
    }
    node = node→next;
}
```

- Pointer based traversal (e.g., of a linked list)
- Assume a huge linked list (1B nodes) and unique keys
- Why does the code on the left have poor cache hit rate?
  - "Other fields" occupy most of the cache line even though rarely accessed!

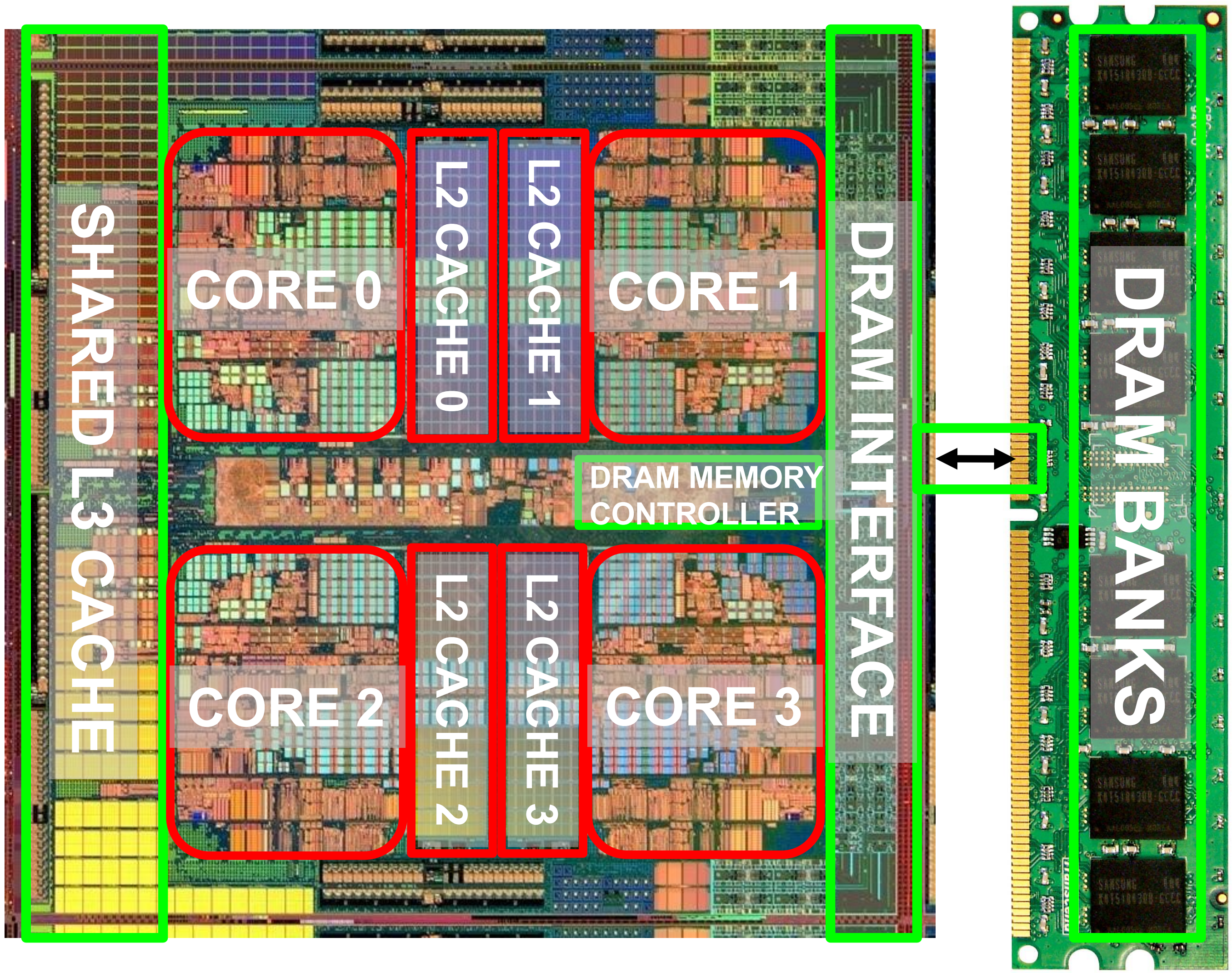
Restructuring Data Layout (II)

```
struct Node {
    struct Node* next;
    int key;
    struct Node-data* node-data;
}

struct Node-data {
    char [256] name;
    char [256] school;
}

while (node) {
    if (node→key == input-key) {
        // access node→node-data
    }
    node = node→next;
}
```

- Idea: separate frequently-used fields of a data structure and pack them into a separate data structure
- Who should do this?
  - Programmer
  - Compiler
    - Profiling vs. dynamic
  - Hardware?
  - Who can determine what is frequently used?

Multi-Core Issues in Caching

Caches in a Multi-Core System



Caches in Multi-Core Systems

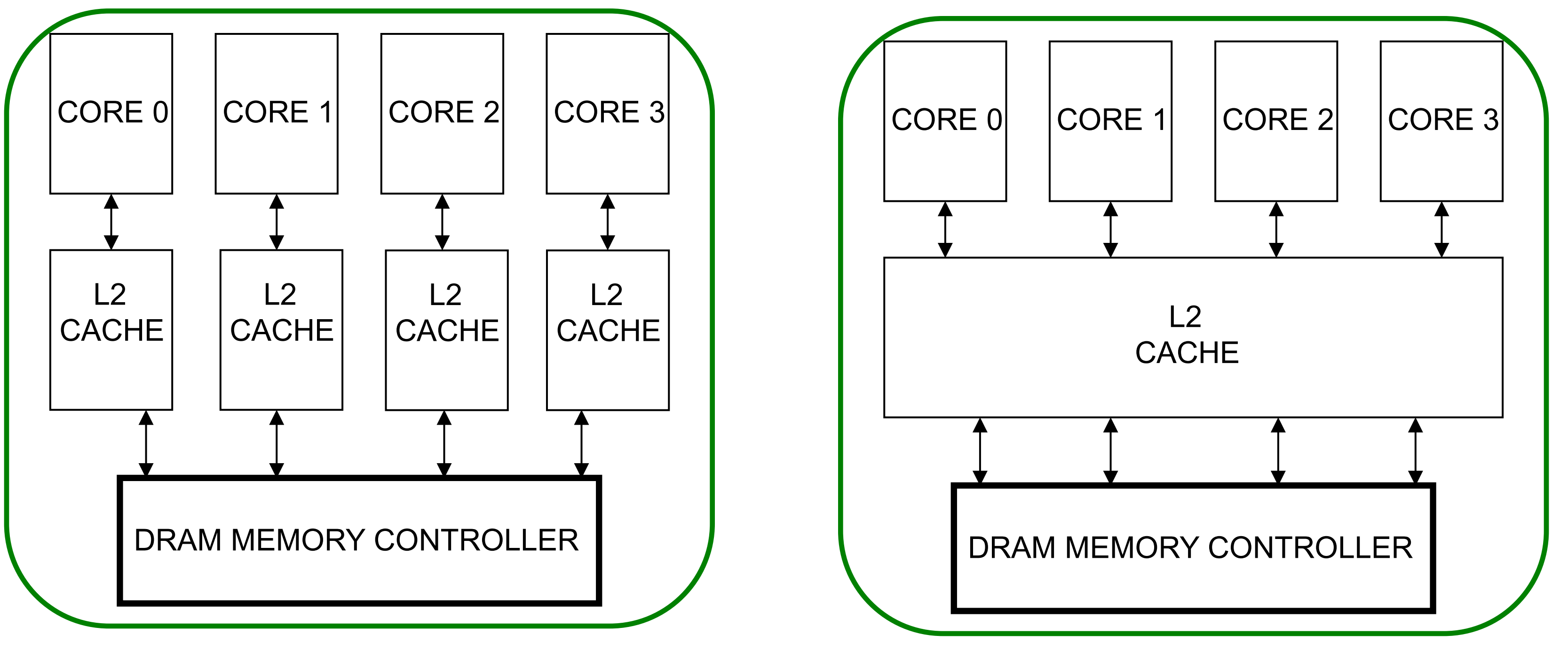
- Cache efficiency becomes even more important in a multi-core/multi-threaded system
  - Memory bandwidth is at premium
  - Cache space is a limited resource across cores/threads

- How do we design the caches in a multi-core system?

- Many decisions
  - Shared vs. private caches
  - How to maximize performance of the entire system?
  - How to provide QoS to different threads in a shared cache?
  - Should cache management algorithms be aware of threads?
  - How should space be allocated to threads in a shared cache?

Private vs. Shared Caches

- Private cache: Cache belongs to one core (a shared block can be in multiple caches)
- Shared cache: Cache is shared by multiple cores



Resource Sharing Concept and Advantages

- Idea: Instead of dedicating a hardware resource to a hardware context, allow multiple contexts to use it
  - Example resources: functional units, pipeline, caches, buses, memory
- Why?

\+ Resource sharing improves utilization/efficiency → throughput
  - When a resource is left idle by one thread, another thread can use it; no need to replicate shared data

\+ Reduces communication latency
  - For example, data shared between multiple threads can be kept in the same cache in multithreaded processors

\+ Compatible with the shared memory programming model

Resource Sharing Disadvantages

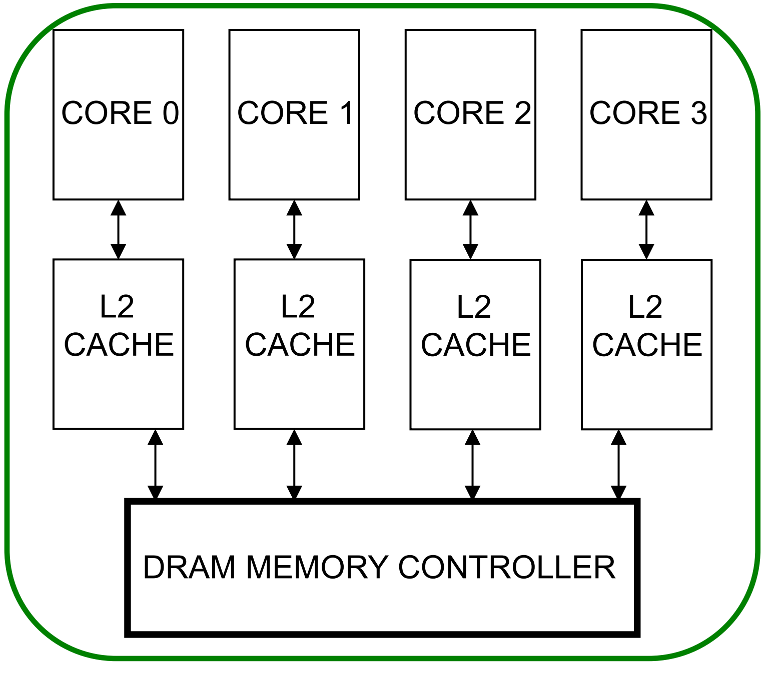
- Resource sharing results in contention for resources
  - When the resource is not idle, another thread cannot use it
  - If space is occupied by one thread, another thread needs to re-occupy it

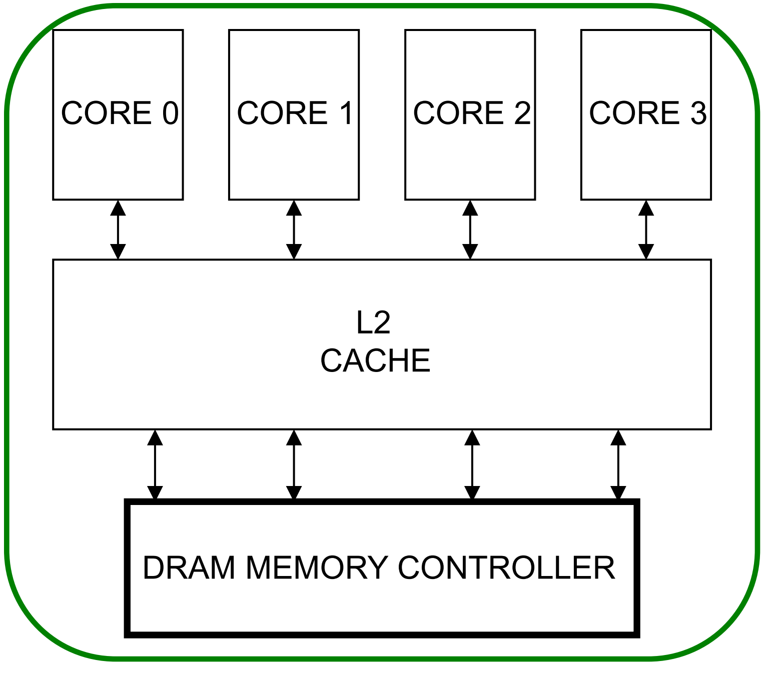
- Sometimes reduces each or some thread's performance
  - Thread performance can be worse than when it is run alone
- Eliminates performance isolation → inconsistent performance across runs
  - Thread performance depends on co-executing threads
- Uncontrolled (free-for-all) sharing degrades QoS
  - Causes unfairness, starvation

Need to efficiently and fairly utilize shared resources

Private vs. Shared Caches

- Private cache: Cache belongs to one core (a shared block can be in multiple caches)
- Shared cache: Cache is shared by multiple cores





Shared Caches Between Cores

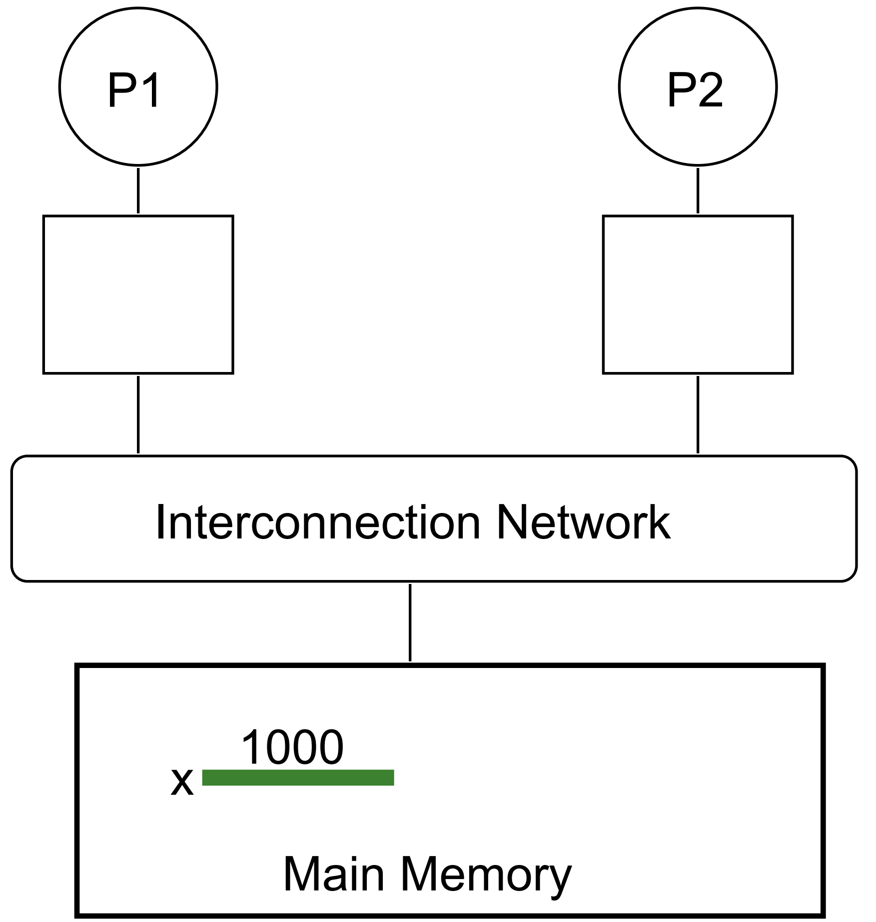
- Advantages:
  - High effective capacity
  - Dynamic partitioning of available cache space
    - No fragmentation due to static partitioning
    - If one core does not utilize some space, another core can
  - Easier to maintain coherence (a cache block is in a single location)

- Disadvantages
  - Slower access (cache not tightly coupled with the core)
  - Cores incur conflict misses due to other cores' accesses
    - Misses due to inter-core interference
    - Some cores can destroy the hit rate of other cores
  - Guaranteeing a minimum level of service (or fairness) to each core is harder (how much space, how much bandwidth?)

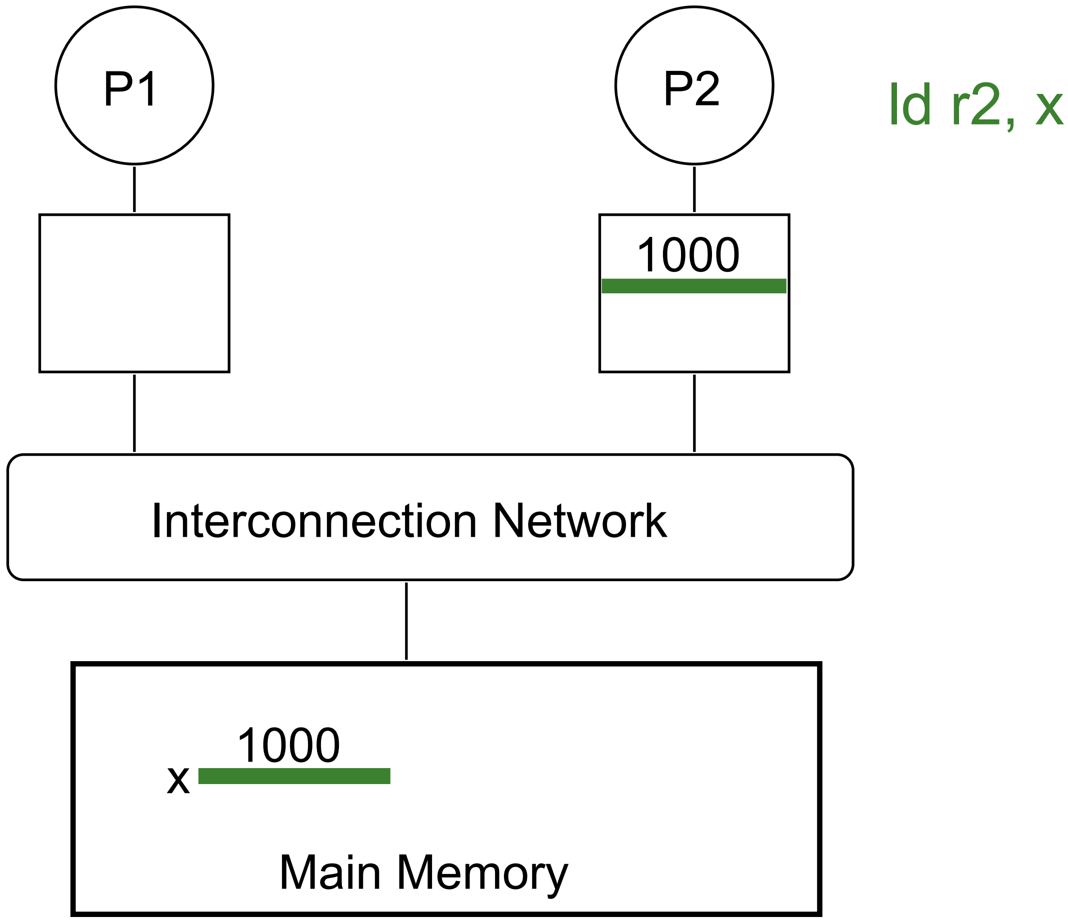
Cache Coherence

Cache Coherence

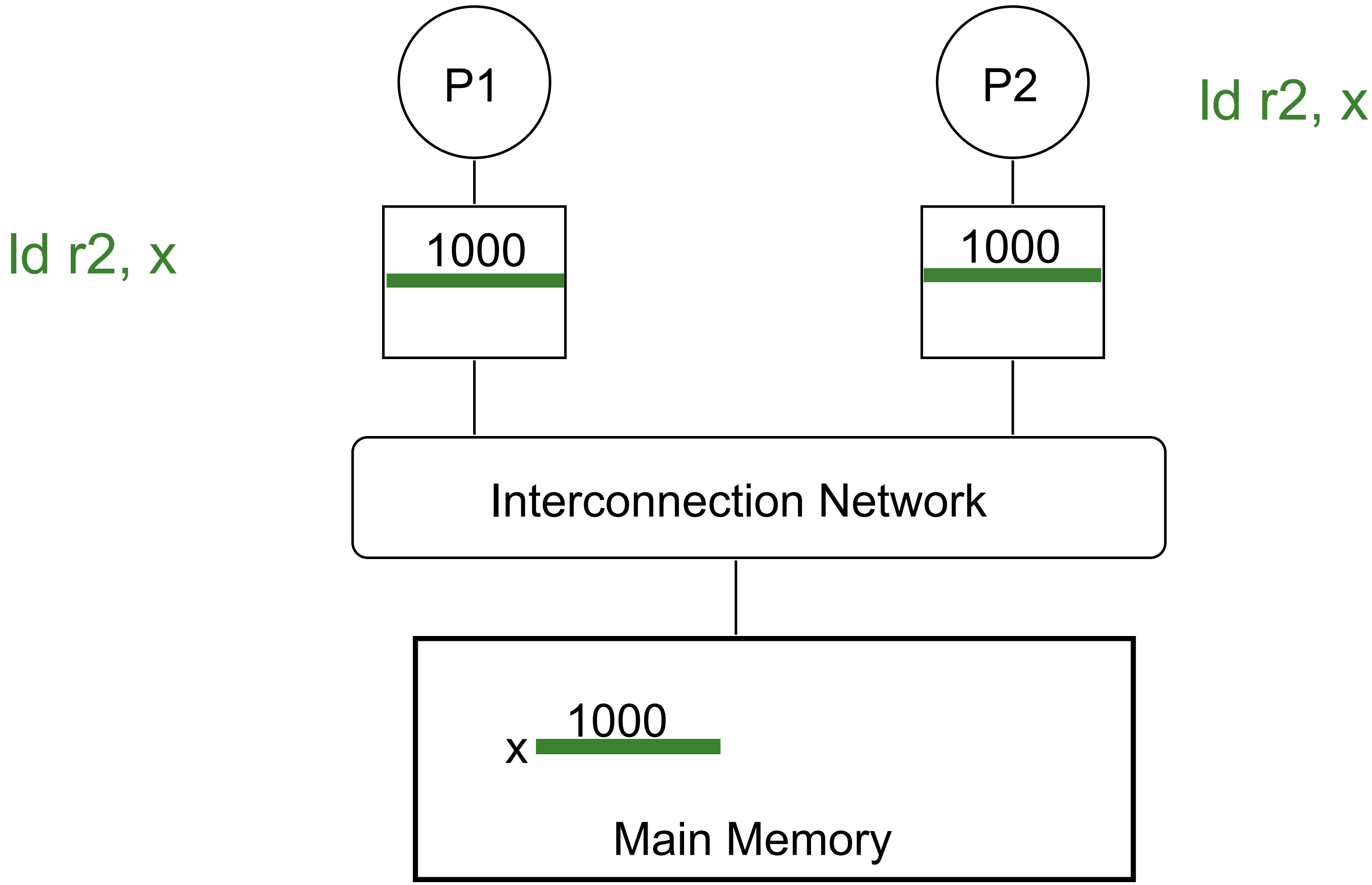
- Basic question: If multiple processors cache the same block, how do they ensure they all see a consistent state?



The Cache Coherence Problem

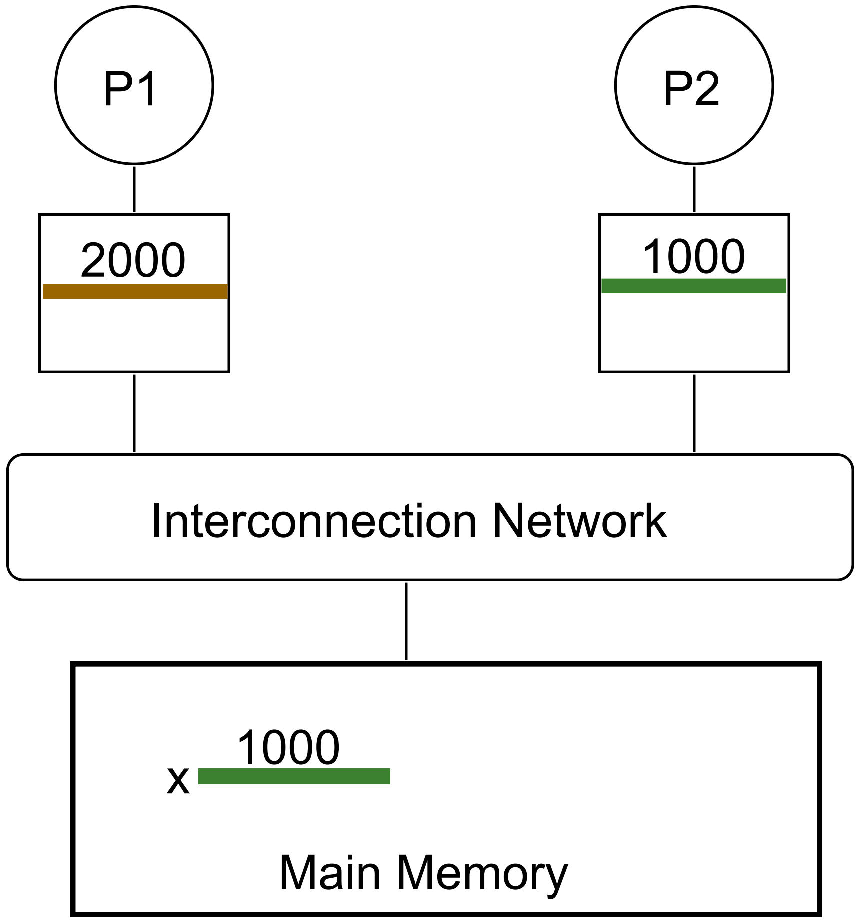


The Cache Coherence Problem



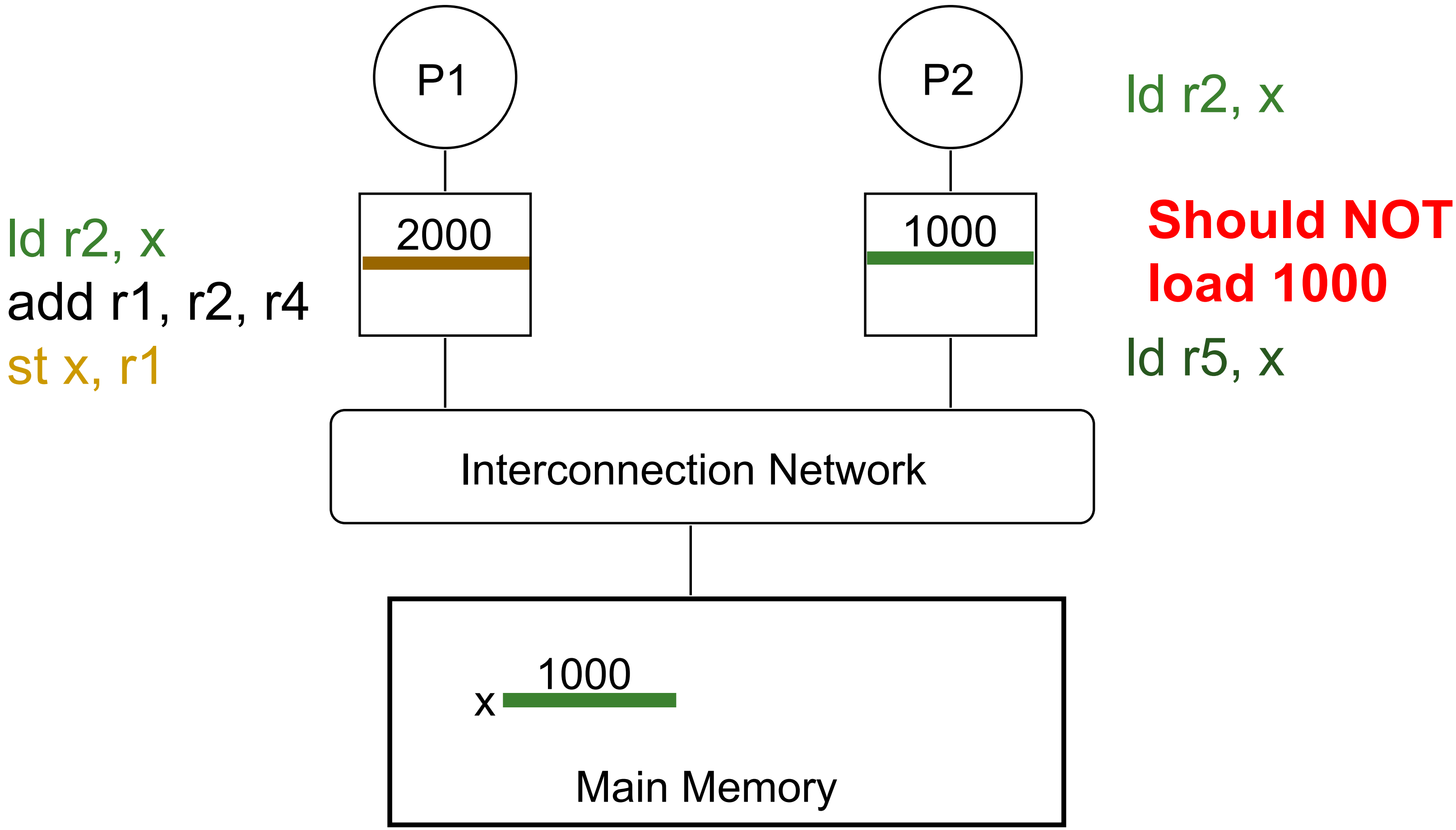
The Cache Coherence Problem

ld r2, x
add r1, r2, r4
st x, r1



ld r2, x

The Cache Coherence Problem



Design of Digital Circuits

Lecture 25a: More Caches

Prof. Onur Mutlu

ETH Zurich

Spring 2018

31 May 2018

Cache Examples: For You to Study

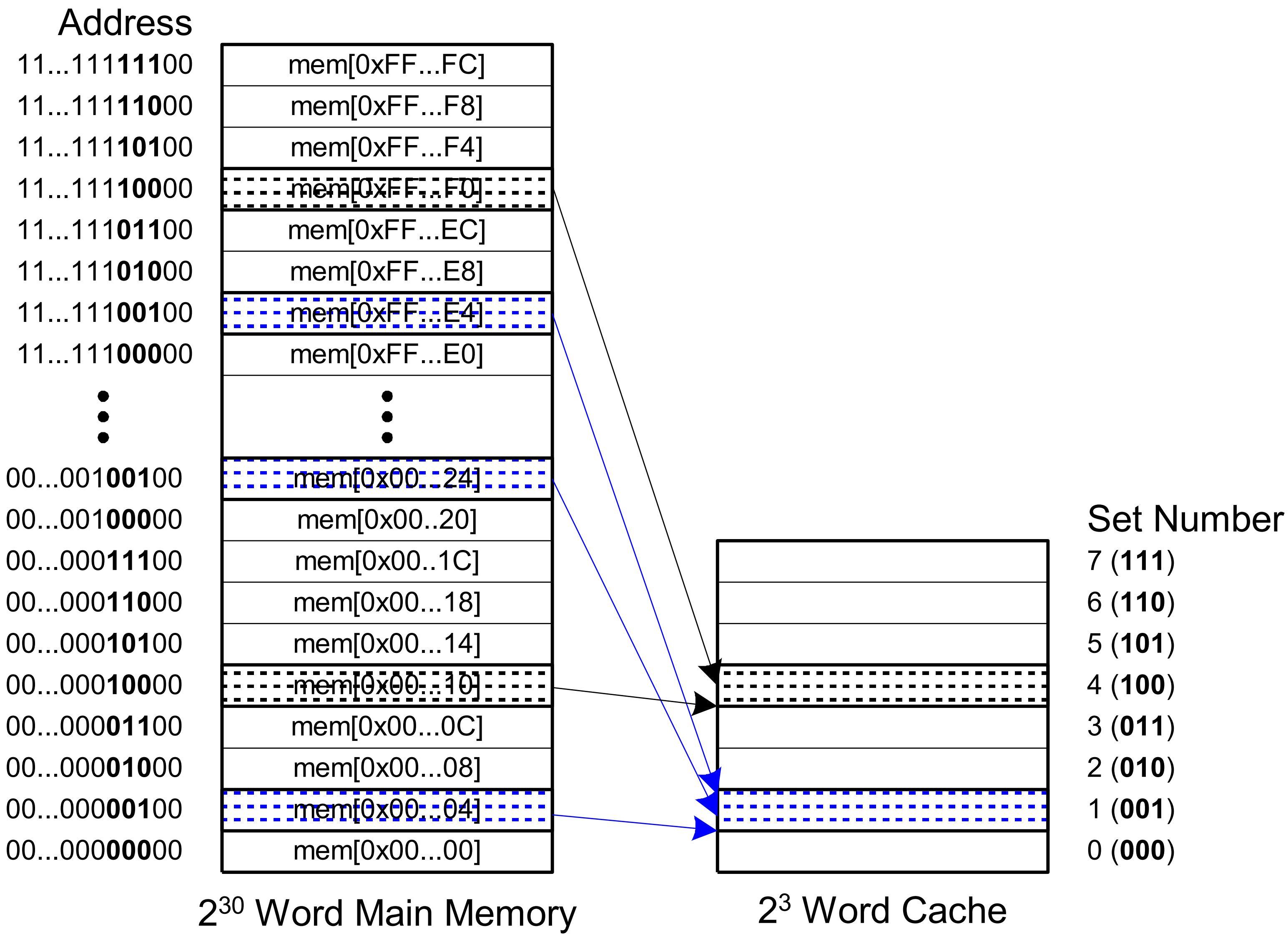
Cache Terminology

- Capacity (*C*):
  - the number of data bytes a cache stores
- Block size (*b*):
  - bytes of data brought into cache at once
- Number of blocks ($B = C/b$):
  - number of blocks in cache: $B = C/b$
- Degree of associativity (*N*):
  - number of blocks in a set
- Number of sets ($S = B/N$):
  - each memory address maps to exactly one cache set

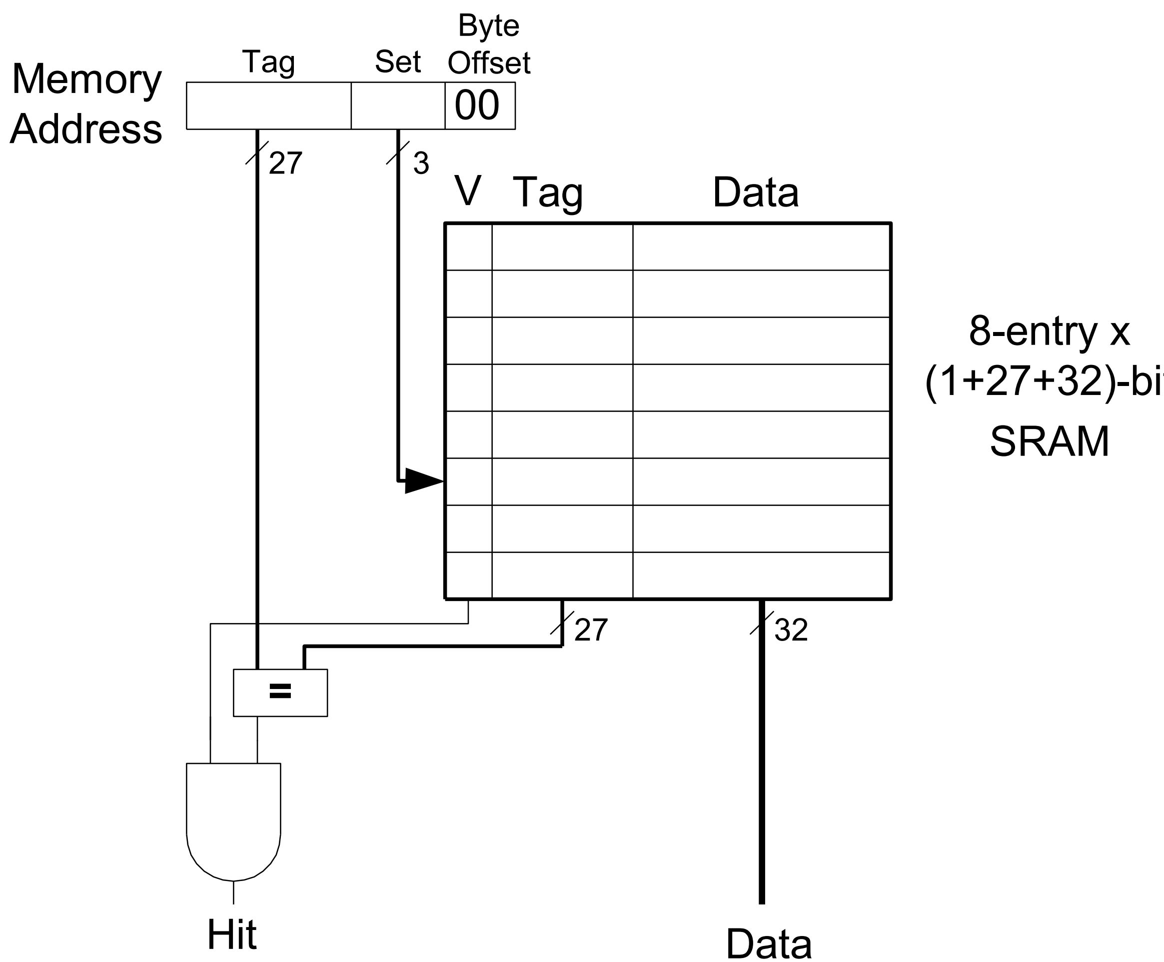
How is data found?

- Cache organized into *S* sets
- Each memory address maps to exactly one set
- Caches categorized by number of blocks in a set:
  - Direct mapped: 1 block per set
  - N-way set associative: N blocks per set
  - Fully associative: all cache blocks are in a single set
- Examine each organization for a cache with:
  - Capacity (C = 8 words)
  - Block size (b = 1 word)
  - So, number of blocks (B = 8)

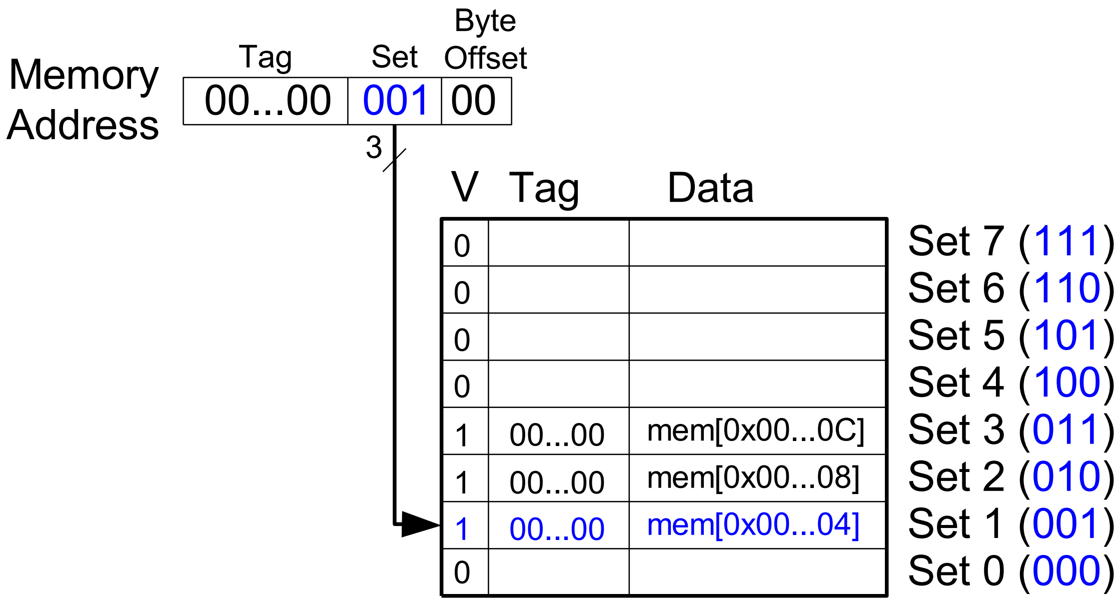
Direct Mapped Cache



Direct Mapped Cache Hardware



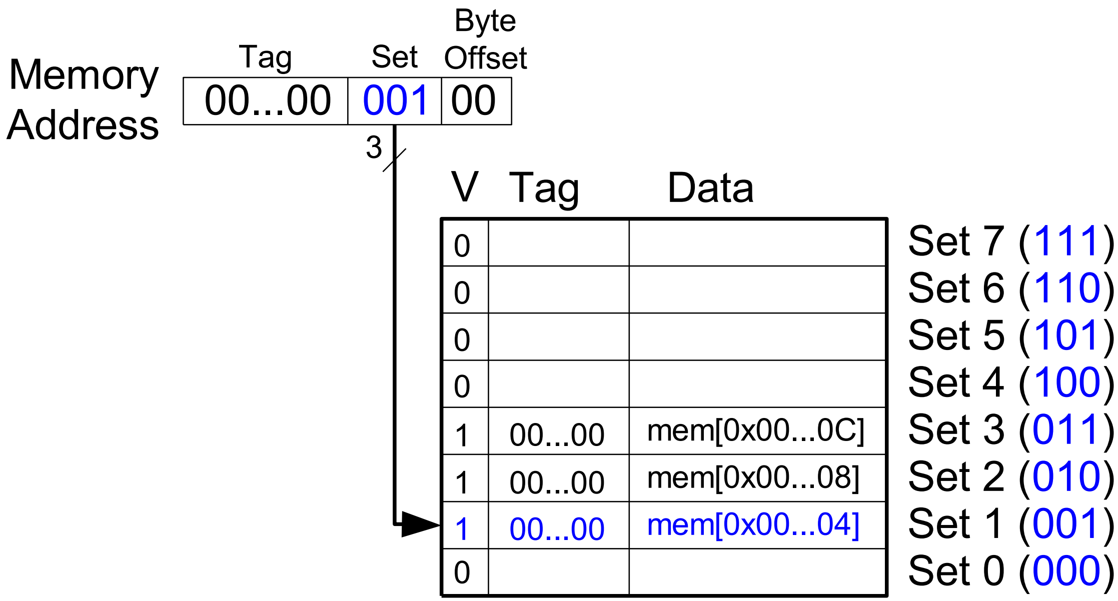
Direct Mapped Cache Performance




```
# MIPS assembly code
        addi $t0, $0, 5
loop:   beq  $t0, $0, done
        lw   $t1, 0x4($0)
        lw   $t2, 0xC($0)
        lw   $t3, 0x8($0)
        addi $t0, $t0, -1
        j    loop
done:
```

Miss Rate =

Direct Mapped Cache Performance

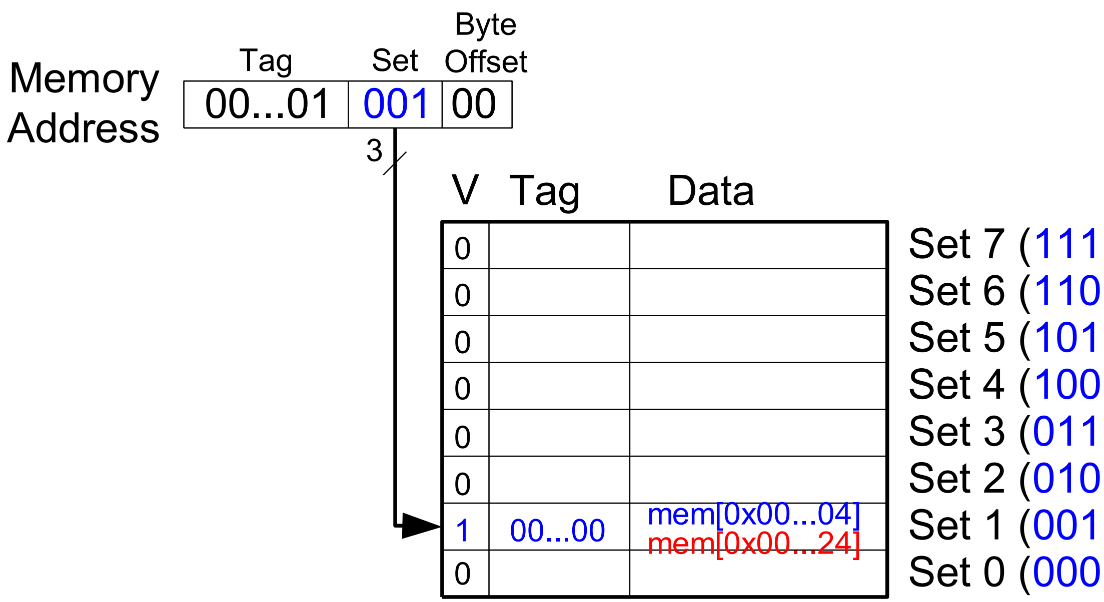



```
# MIPS assembly code
        addi $t0, $0, 5
loop:   beq  $t0, $0, done
        lw   $t1, 0x4($0)
        lw   $t2, 0xC($0)
        lw   $t3, 0x8($0)
        addi $t0, $t0, -1
        j    loop
done:
```

Miss Rate = 3/15 = 20%

Temporal Locality
Compulsory Misses

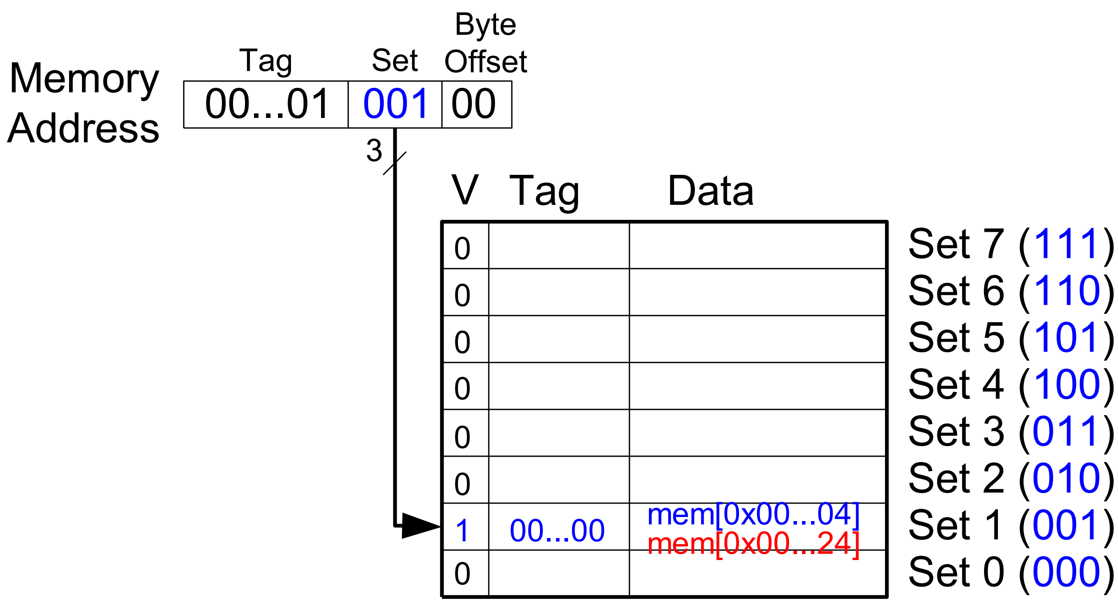
Direct Mapped Cache: Conflict




```
# MIPS assembly code
        addi $t0, $0, 5
loop:   beq  $t0, $0, done
        lw   $t1, 0x4($0)
        lw   $t2, 0x24($0)
        addi $t0, $t0, -1
        j    loop
done:
```

Miss Rate =

Direct Mapped Cache: Conflict

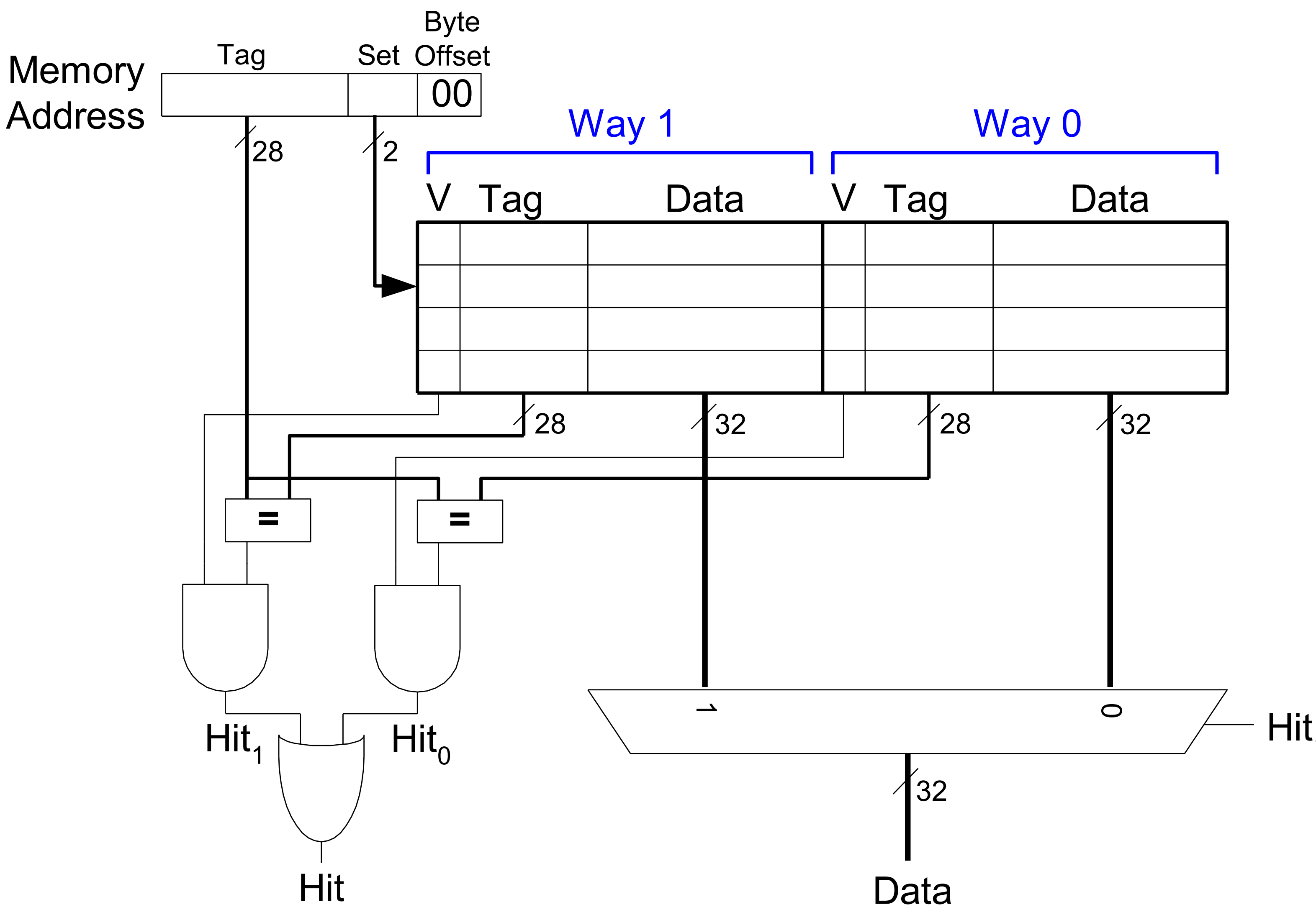



```
# MIPS assembly code
        addi $t0, $0, 5
loop:   beq  $t0, $0, done
        lw   $t1, 0x4($0)
        lw   $t2, 0x24($0)
        addi $t0, $t0, -1
        j    loop
done:
```

Miss Rate = 10/10
= 100%

Conflict Misses

N-Way Set Associative Cache



N-way Set Associative Performance

```
# MIPS assembly code

        addi $t0, $0, 5
loop:   beq  $t0, $0, done
        lw   $t1, 0x4($0)
        lw   $t2, 0x24($0)
        addi $t0, $t0, -1
        j    loop
done:
```

Miss Rate =

Way 1 V	Way 1 Tag	Way 1 Data	Way 0 V	Way 0 Tag	Way 0 Data	
0			0			Set 3
0			0			Set 2
1	00...10	mem[0x00...24]	1	00...00	mem[0x00...04]	Set 1
0			0			Set 0

N-way Set Associative Performance

```
# MIPS assembly code

        addi $t0, $0, 5
loop:   beq  $t0, $0, done
        lw   $t1, 0x4($0)
        lw   $t2, 0x24($0)
        addi $t0, $t0, -1
        j    loop
done:
```

Miss Rate = 2/10

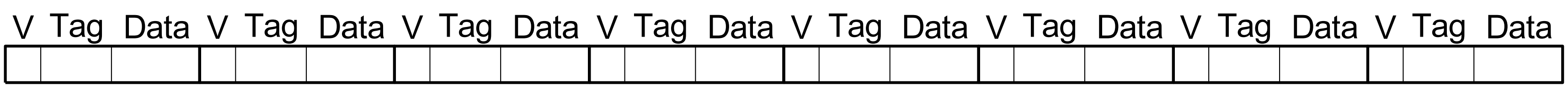
= 20%

Associativity reduces conflict misses

Way 1 V	Way 1 Tag	Way 1 Data	Way 0 V	Way 0 Tag	Way 0 Data	
0			0			Set 3
0			0			Set 2
1	00...10	mem[0x00...24]	1	00...00	mem[0x00...04]	Set 1
0			0			Set 0

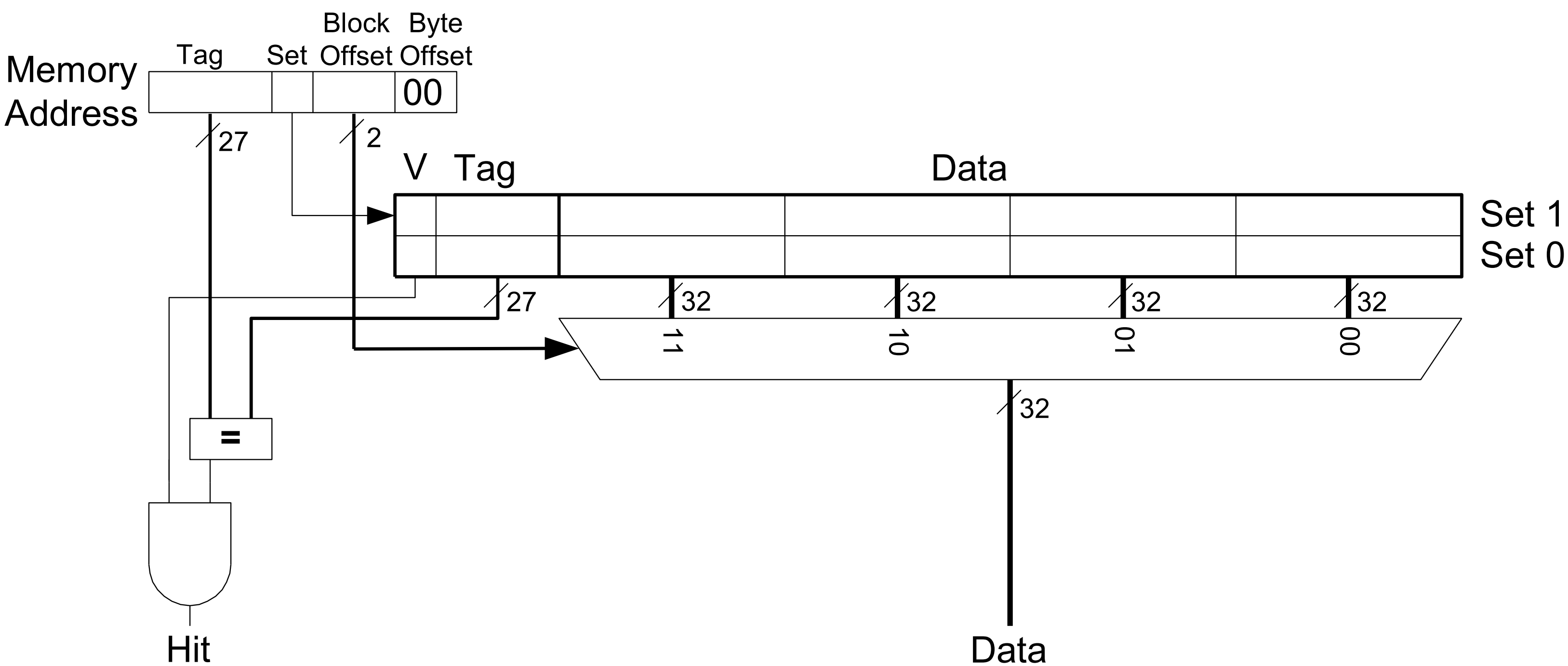
Fully Associative Cache

- No conflict misses
- Expensive to build



Spatial Locality?

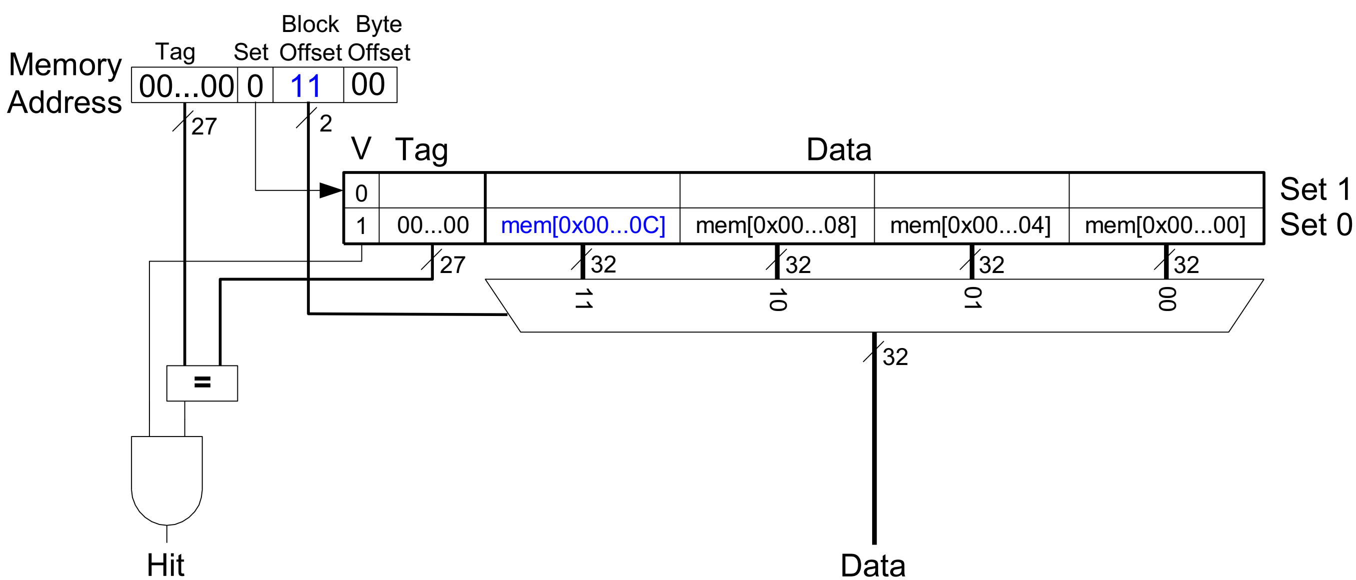
- Increase block size:
  - Block size, ***b* = 4** words
  - C = 8 words
  - Direct mapped (1 block per set)
  - Number of blocks, $B = C/b = 8/4 = 2$



Direct Mapped Cache Performance

```
        addi $t0, $0, 5
loop:   beq  $t0, $0, done
        lw   $t1, 0x4($0)
        lw   $t2, 0xC($0)
        lw   $t3, 0x8($0)
        addi $t0, $t0, -1
        j    loop
done:
```

Miss Rate =



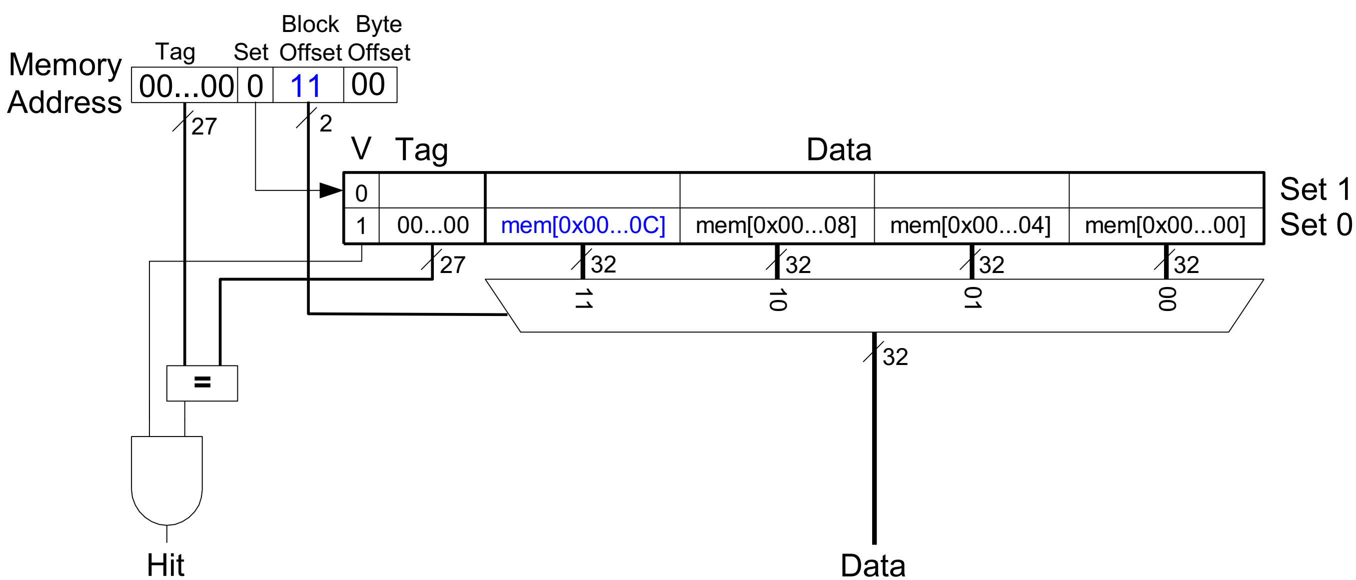
Direct Mapped Cache Performance

```
        addi $t0, $0, 5
loop:   beq  $t0, $0, done
        lw   $t1, 0x4($0)
        lw   $t2, 0xC($0)
        lw   $t3, 0x8($0)
        addi $t0, $t0, -1
        j    loop
done:
```

Miss Rate = 1/15

= 6.67%

Larger blocks reduce compulsory misses through spatial locality



Cache Organization Recap

- Main Parameters
  - Capacity: ***C***
  - Block size: ***b***
  - Number of blocks in cache: ***B*** = C/b
  - Number of blocks in a set: ***N***
  - Number of Sets: ***S*** = B/N

Organization	Number of Ways (N)	Number of Sets (S = B/N)
Direct Mapped	1	B
N-Way Set Associative	1 < N < B	B / N
Fully Associative	B	1

Capacity Misses

- Cache is too small to hold all data of interest at one time
  - If the cache is full and program tries to access data X that is not in cache, cache must evict data Y to make room for X
  - **Capacity miss** occurs if program then tries to access Y again
  - X will be placed in a particular set based on its address

- In a direct mapped cache, there is only one place to put X

- In an associative cache, there are multiple ways where X could go in the set.

- How to choose Y to minimize chance of needing it again?
  - Least recently used (LRU) replacement: the least recently used block in a set is evicted when the cache is full.

Types of Misses

- Compulsory: first time data is accessed
- Capacity: cache too small to hold all data of interest
- Conflict: data of interest maps to same location in cache
- Miss penalty: time it takes to retrieve a block from lower level of hierarchy

LRU Replacement

```
# MIPS assembly

lw $t0, 0x04($0)
lw $t1, 0x24($0)
lw $t2, 0x54($0)
```

(a)

V	U	Tag	Data	V	Tag	Data	Set Number
							3 (**11**)
							2 (**10**)
							1 (**01**)
							0 (**00**)

(b)

V	U	Tag	Data	V	Tag	Data	Set Number
							3 (**11**)
							2 (**10**)
							1 (**01**)
							0 (**00**)

LRU Replacement

```
# MIPS assembly

lw $t0, 0x04($0)
lw $t1, 0x24($0)
lw $t2, 0x54($0)
```

(a)

Way 1 V	Way 1 U	Way 1 Tag	Way 1 Data	Way 0 V	Way 0 Tag	Way 0 Data	
0	0			0			Set 3 (11)
0	0			0			Set 2 (10)
1	0	00...010	mem[0x00...24]	1	00...000	mem[0x00...04]	Set 1 (01)
0	0			0			Set 0 (00)

(b)

Way 1 V	Way 1 U	Way 1 Tag	Way 1 Data	Way 0 V	Way 0 Tag	Way 0 Data	
0	0			0			Set 3 (11)
0	0			0			Set 2 (10)
1	1	00...010	mem[0x00...24]	1	00...101	mem[0x00...54]	Set 1 (01)
0	0			0			Set 0 (00)