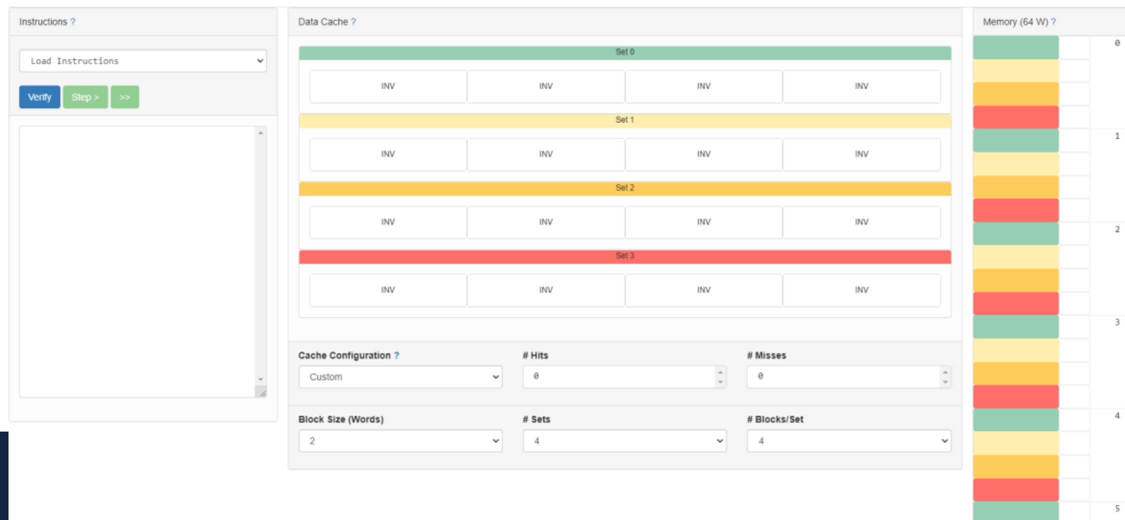
EECS 370

Classifying Cache Misses

Announcements

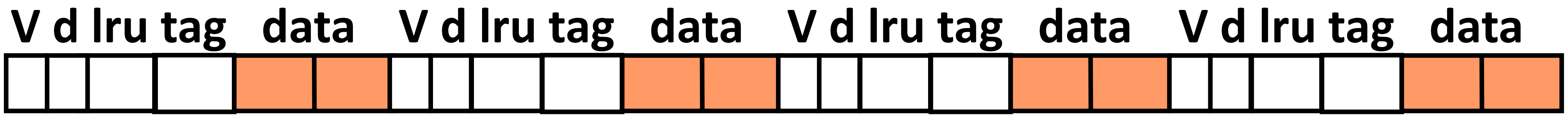
- Don't forget pre-lab quiz tonight!
- P3 due tomorrow
- P4 released in the next day
  - checkout cache simulator on website!
- HW 3 due Monday
- Bonus lecture Thursday



Cache Organization Comparison

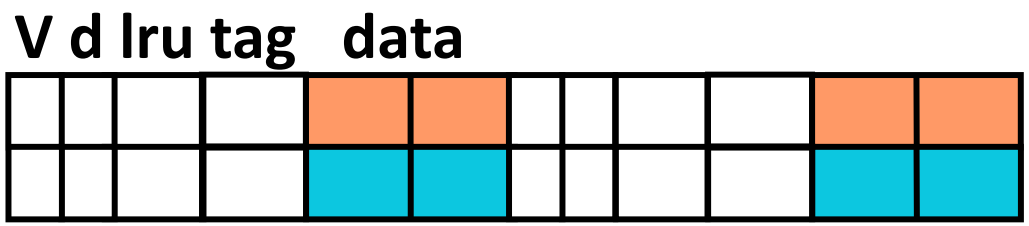
Block size = 2 bytes, total cache size = 8 bytes for all caches

1. Fully associative (4-way associative)



2. Direct mapped

3. 2-way associative



Set-associative cache (REF 4)

Poll: Finish the remaining references

https://bit.ly/3x7nKpP

Processor

- Ld R1 ← M[1]
- Ld R2 ← M[5]
- St R2 → M[7]
- St R1 → M[4]
- Ld R3 ← M[0]
- Ld R2 ← M[8]

R0	
R1	29
R2	150
R3	

Cache

	V	d	tag	data
lru	1	0	0	78
				29
	1	0	1	71
				150
	1	1	1	162
				150
lru	0			

Misses: 3

Hits: 0

Memory

0	78
1	29
2	120
3	123
4	71
5	150
6	162
7	173
8	18
9	21
10	33
11	28
12	19
13	200
14	210
15	225

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Set-associative cache (REF 5)

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Cache

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	1	1	1	162
				150
lru	0			

Misses: 3

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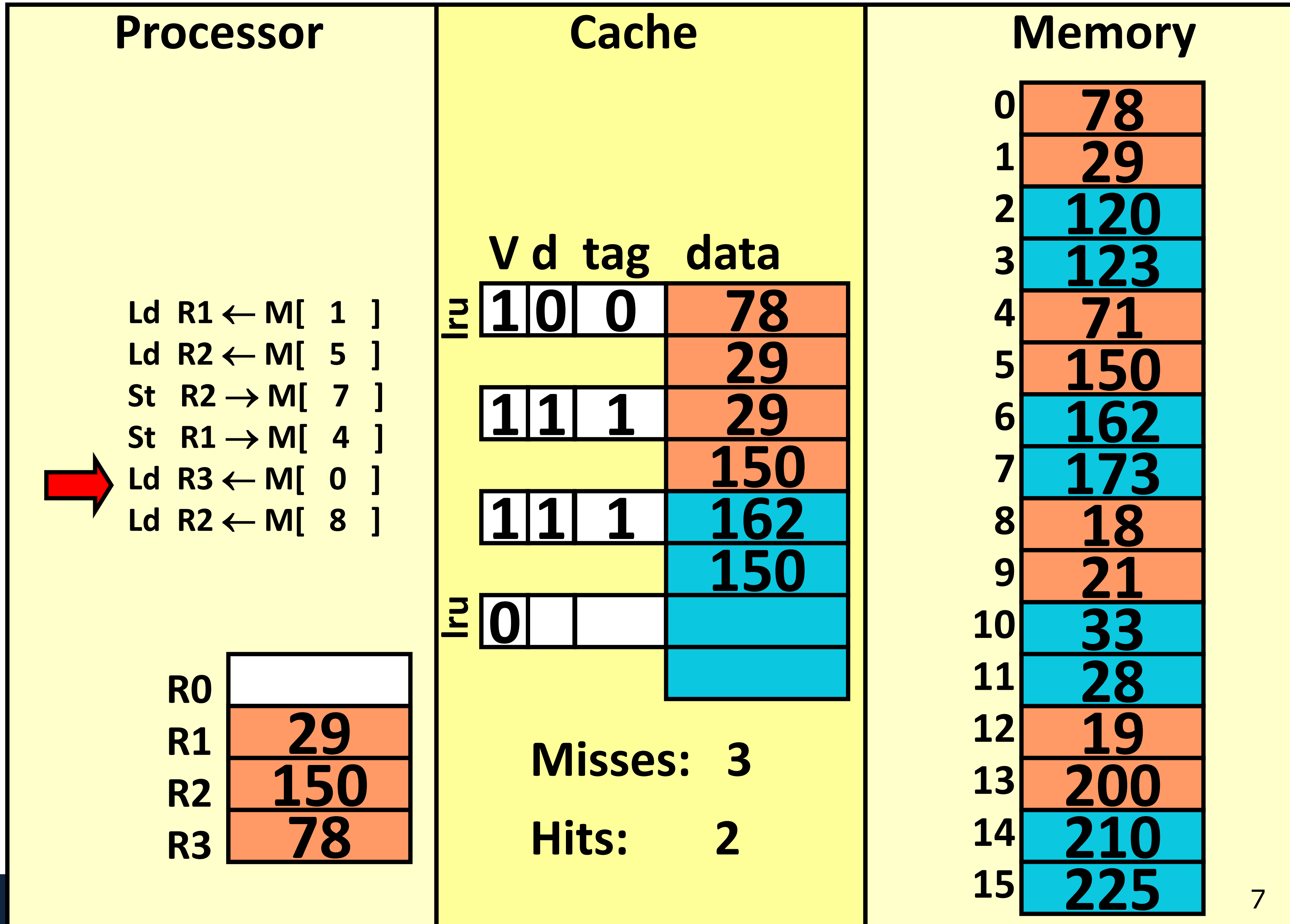
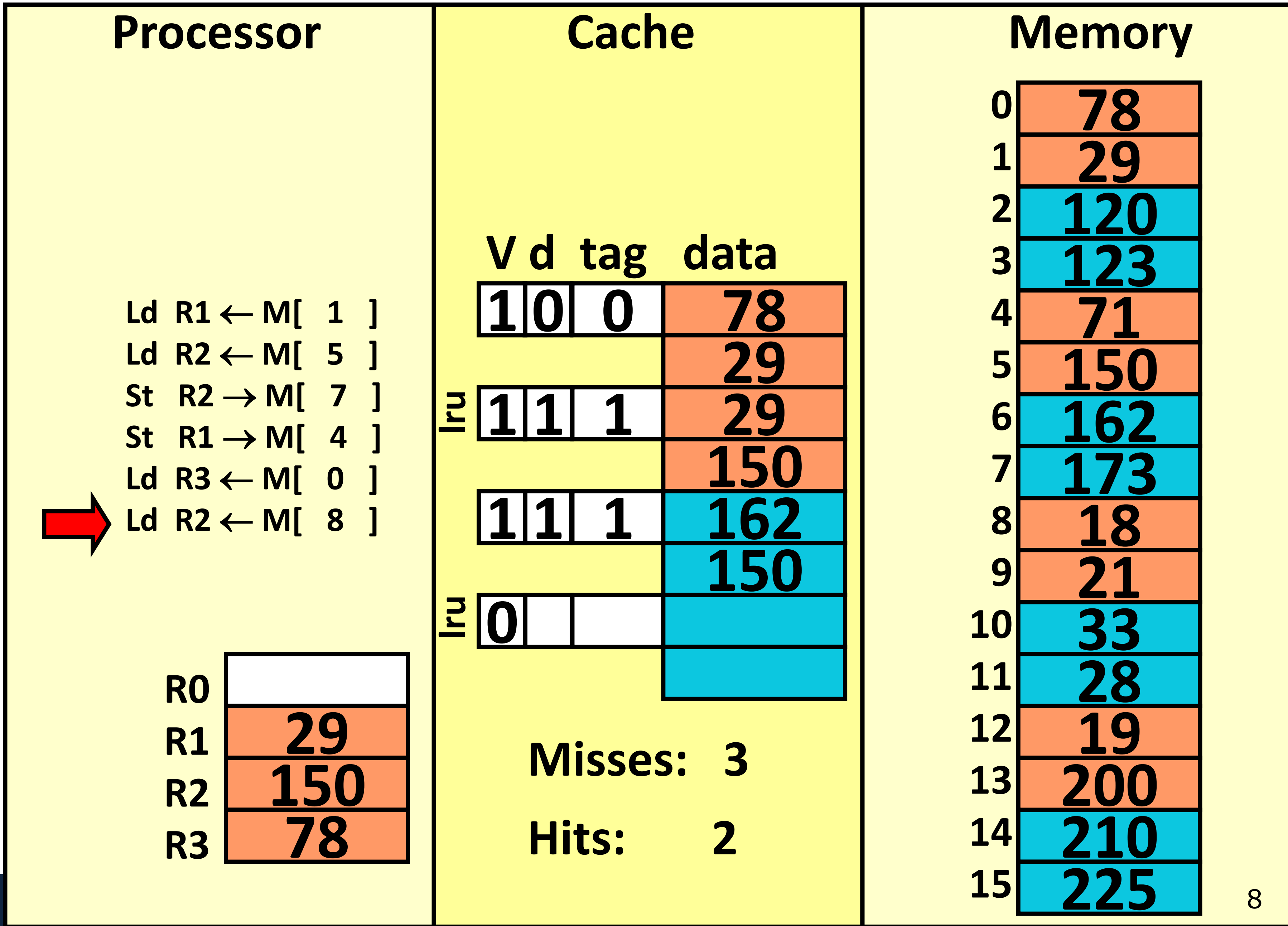
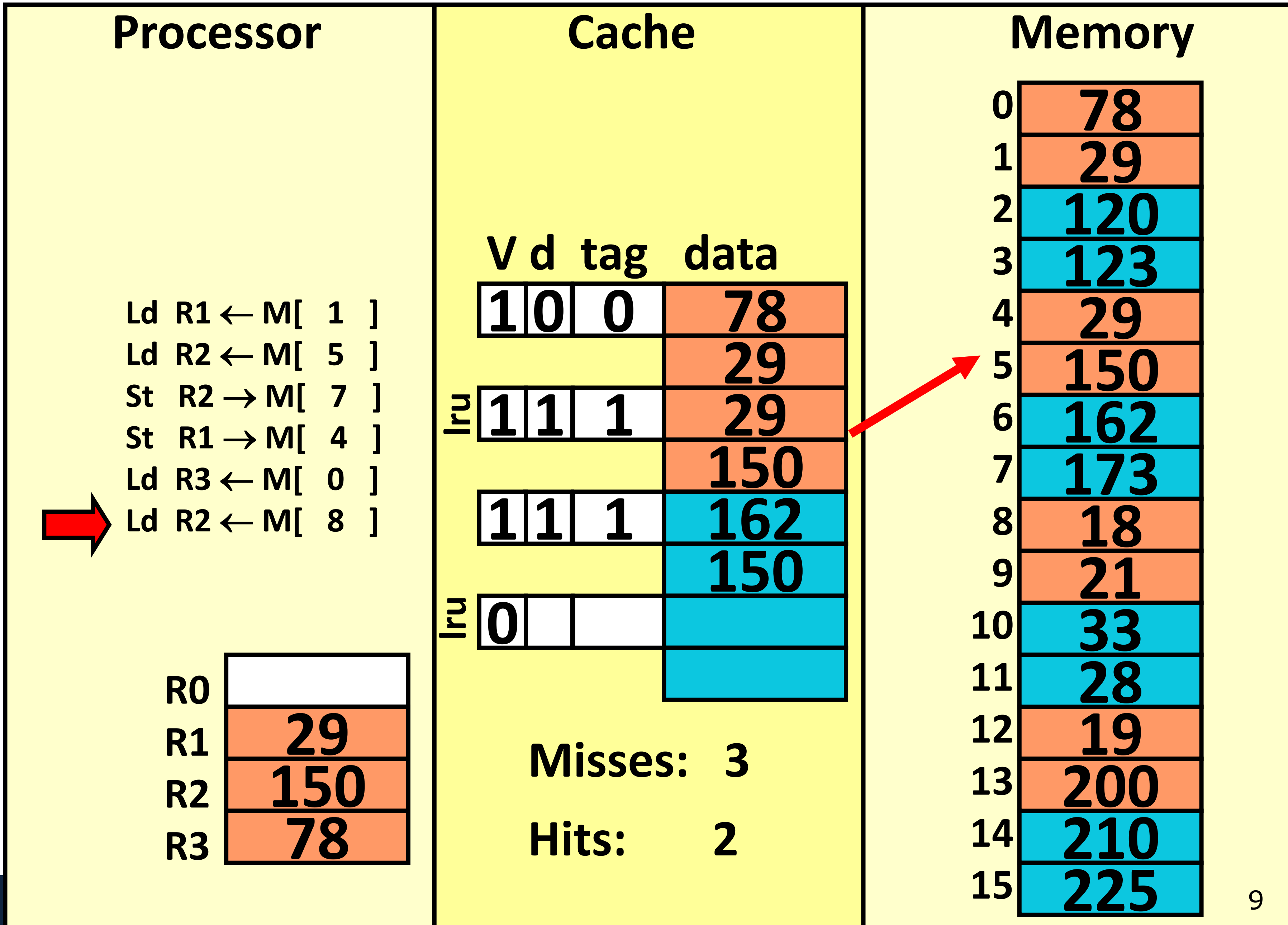


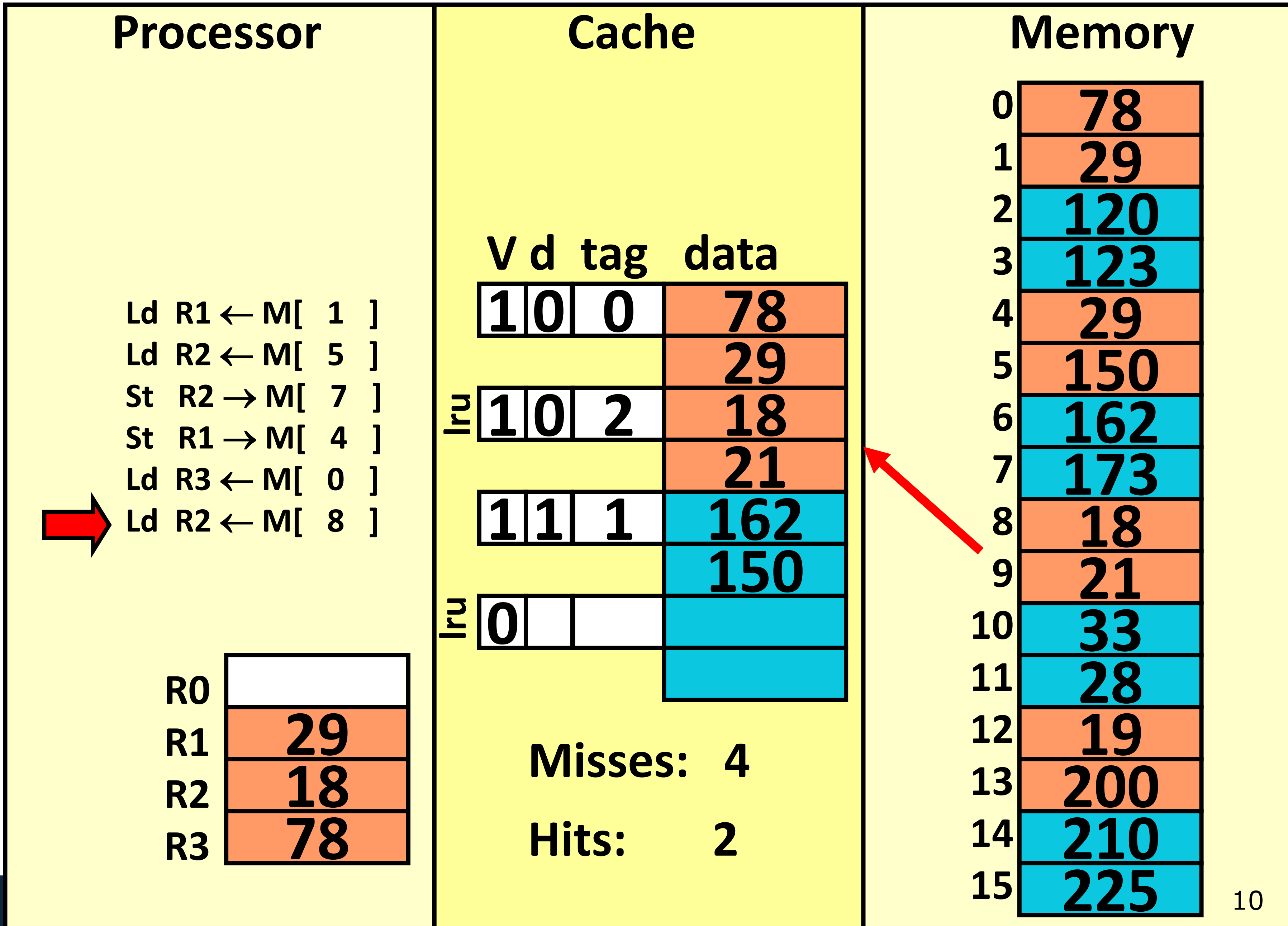
Set-associative cache (REF 6)



Set-associative cache (REF 6)



Set-associative cache (REF 6)



Agenda

- Set-associativity overview
- Example
- **Class problem**
- Integrating caches into our processor

Class Problem 1

- For a 32-bit address and 16KB cache with 64-byte blocks, show the breakdown of the address for the following cache configuration:

A) fully associative cache

B) 4-way set associative cache

C) Direct-mapped cache

Class Problem 1

- For a 32-bit address and 16KB cache with 64-byte blocks, show the breakdown of the address for the following cache configuration:

A) fully associative cache

Block Offset = log2(64)=6 bits
Tag = 32 - 6 = 26 bits

B) 4-way set associative cache

Block Offset = 6 bits
#sets = #lines / ways = 64
Set Index = 6 bits
Tag = 32 - 6 - 6 = 20 bits

C) Direct-mapped cache

Block Offset = 6 bits
#lines = 256 Line Index = 8 bits
Tag = 32 – 6 – 8 = 18 bits

Agenda

- Set-associativity overview
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- **Integrating caches into our processor**

Multi-Level Caches

- We've been considering proc -> cache -> memory

- This works well if working data set is <= size of cache

- But if data set is a little larger that cache, performance can plummet

Multi-Level Caches

- This is the motivation of multiple levels of caches
- L1 – smallest, fastest, closest to processor
- LN – biggest, slowest, closest to memory
- Allows for gradual performance degradation as data set size increases
- 3 levels of cache is pretty common in today's systems

What about cache for instructions

- We've been focusing on caching loads and stores (i.e. data)
- Instructions should be cached as well
- We have two choices:
  1. Treat instruction fetches as normal data and allocate cache lines when fetched
  2. Create a second cache (called the instruction cache or ICache) which caches instructions only
     - More common in practice

How do you know which cache to use?

What are advantages of a separate ICache?

Integrating Caches into Pipeline

- How are caches integrated into a pipelined implementation?
  - Replace instruction memory with Icache
  - Replace data memory with Dcache

- Issues:
  - Memory accesses now have variable latency
  - Both caches may miss at the same time

Agenda

- **Motivation**
- Example
- How to optimize cache design
- Practice Problem 1
- Practice Problem 2
- Practice Problem 3
- Practice Problem 4

Improving our Caches

- If our cache is getting a lot of misses, how do we improve it?
  - Depends on why the misses occurring
  - Is the cache too small? Is the associativity too restrictive? Something else?
- A decent first step is to **classify** the types of missing we are observing

Classifying Cache Misses

- Cache misses happen for 3* reasons
  - The 3C's of Cache misses:
- Compulsory miss
  - We've never accessed this data before
- Capacity miss
  - Cache is not large enough to hold all the data
  - May have been avoided if we used a bigger cache
- Conflict miss
  - Cache is large enough to hold data, but was replaced due to overly restrictive associativity
  - May have been avoided if we used a higher-associative cache

Note: *On multi-core systems, there's a 4th C – take EECS 470/570 to learn more*

Classifying Cache Misses

- Scenario: run given program on system with N-way cache of size M
  - Identify each miss
- We can classify each miss in a program by simulating on 3 different caches
  - If miss still occurs in cache where size >= memory size: compulsory miss
  - Else, if miss occurs in fully associative cache of size M: capacity miss
  - Else, if miss occurs in N-way cache of size M (original cache): conflict miss

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3C's Sample Problem

Consider a cache with the following configuration: write-allocate, total size is 64 bytes, block size is 16 bytes, and 2-way associative. The memory address size is 16 bits and byte-addressable. The replacement policy is LRU. The cache is empty at the start.

For the following memory accesses, indicate whether the reference is a hit or miss, and the type of a miss (compulsory, conflict, capacity)

3 C's Practice Problem – 3 C's

64 bytes total, 16 byte blocks, 2-way, 2 sets

Address	Infinite	FA	SA	3Cs
0x00				
0x14				
0x27				
0x08				
0x38				
0x4A				
0x18				
0x27				
0x0F				
0x40				

3 C's Practice Problem – 3 C's

Poll: How many blocks will be in a 64 byte FA cache?

Address	Infinite	FA	SA	3Cs
0x00	M			
0x14	M			
0x27	M			
0x08	H			
0x38	M			
0x4A	M			
0x18	H			
0x27	H			
0x0F	H			
0x40	H			

3 C's Practice Problem – 3 C's

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3 C's Practice Problem – 3 C's

64 bytes total, 16 byte blocks, 2-way, 2 sets

Address	Infinite	FA	SA	3Cs
0x00	M	M	M	Compulsory
0x14	M	M	M	Compulsory
0x27	M	M	M	Compulsory
0x08	H	H	H	---
0x38	M	M	M	Compulsory
0x4A	M	M	M	Compulsory
0x18	H	M	H	---
0x27	H	M	M	Capacity
0x0F	H	M	M	Capacity
0x40	H	H	M	Conflict

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How to reduce cache misses

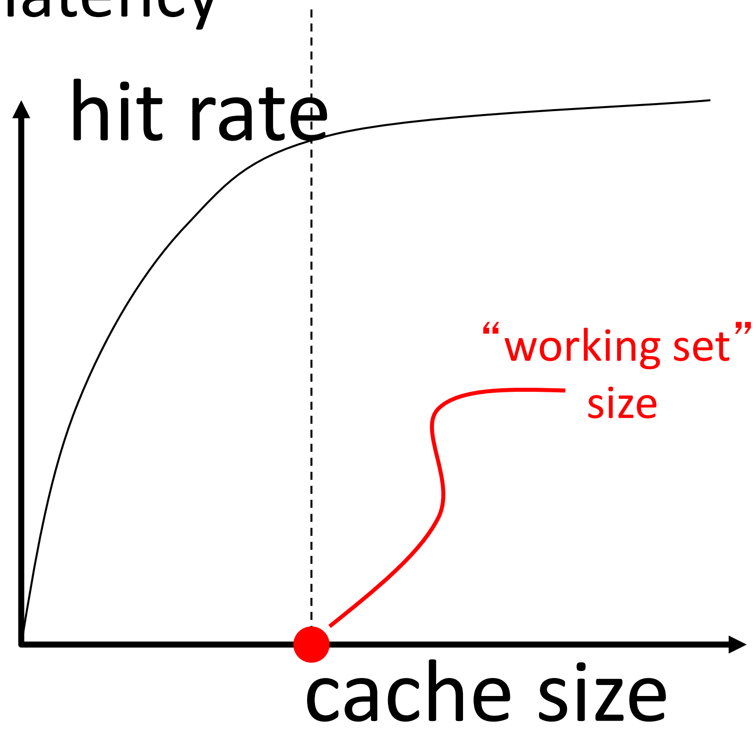
- Compulsory miss
  - Reduce by **increasing cache block size**
    - Reduces total number of blocks for given cache size ☹
  - Or by using prefetching (guess we'll need data based on previous memory patterns - discussed more in EECS 470)
- Capacity miss
  - Reduce by **building a bigger cache**
    - Increase access latency ☹
- Conflict miss
  - Reduce by **increasing associativity**
    - Increase access latency / overheads ☹

Cache Performance

- How does changing these parameters affect performance?
  - Cache size
  - Block size
  - Associativity

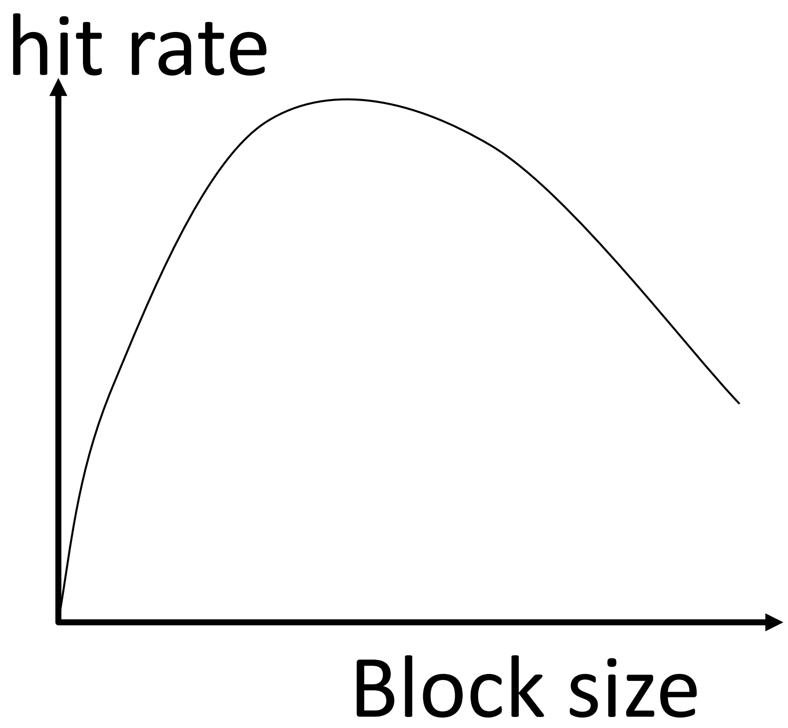
Cache Size

- Cache size in the total data (not including tag) capacity
  - bigger can exploit temporal locality better
  - not ALWAYS better
- Too large a cache adversely affects hit & 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 executing application references
  - **Within a time interval**



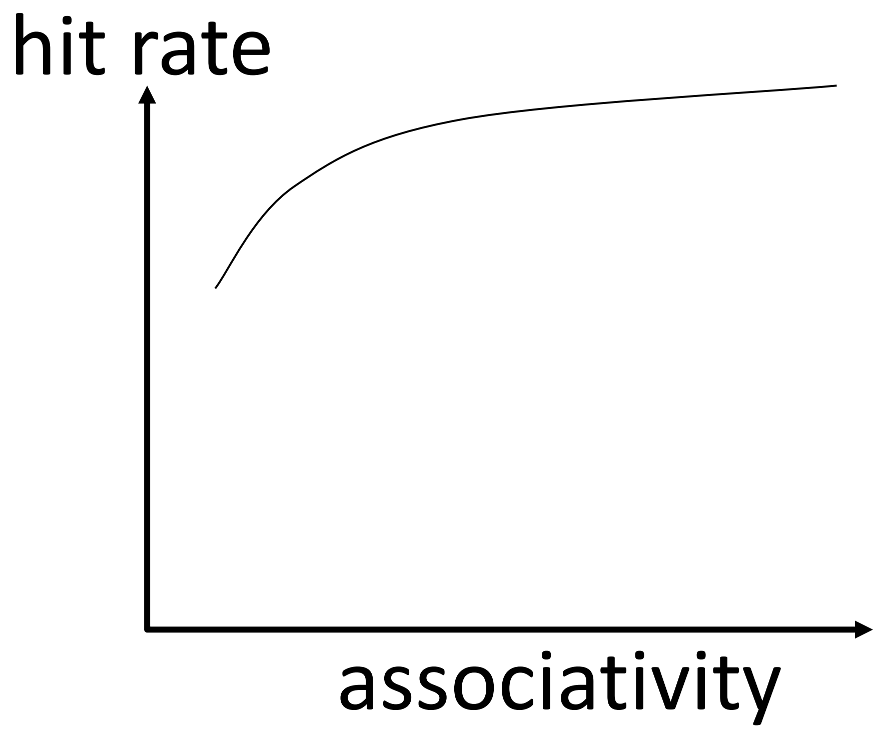
Block size

- Block size is the data that is associated with an address tag
  - Sub-blocking: A block divided into multiple pieces (each with V bit)
    - Can improve “write” performance
    - Take 470 to learn more
- Too small blocks
  - don’t exploit spatial locality well
  - have larger tag overhead
- Too large blocks
  - too few total # of blocks
    - likely-useless data transferred
    - Extra bandwidth/energy consumed



Associativity

- How many blocks can map to the same index (or set)?
- Larger associativity
  - lower miss rate, less variation among programs
  - diminishing returns



- Smaller associativity
  - lower cost
  - faster hit time
    - Especially important for L1 caches

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<u>Poll:</u> What is the CPI increase over base (1) due to hazards?

Practice Problem 1: CPI with caches

The *blaster* application run on the LC2k with full data forwarding and all branches predicted not-taken has the following instruction frequencies:

45% R-type 20% Branches 15% Loads 20% Stores

In *blaster*, 40% of branches are taken and 50% of LWs are followed by an immediate use.

The I-cache has a miss rate of 3% and the D-cache has a miss rate of 6% (no overlapping of misses). On a miss, the main memory is accessed and has a latency of 100 ns. The clock frequency is 500 MHz.

Problem 1 Solution

The *blaster* application run on the LC2k with full data forwarding and all branches predicted not-taken has the following instruction frequencies:

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What is the CPI of *blaster* on the LC2k?

Stalls per cache miss = 100 ns / 2ns = 50 cycles (500 Mhz → 2ns cycle time)

CPI = 1 + data hazard stalls + control hazard stalls + icache stalls + dcache stalls

CPI = 1 + 0.15*0.50*1 + 0.20*0.40*3 + 1*0.03*50 + 0.35*0.06*50

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Poll: How many bytes are read/written if we have no cache?

Practice Problem 2: Memory Usage

- Say you have the following:
  - A program that generates 2 Billion loads and 1 Billion stores, each 4 bytes in size.
  - A cache with a 32-byte block which gets a 95% hit rate on that program.

- How many bytes of memory would be read and written if:
  - We had no cache?
  - We had a write-though cache with a no-write allocate policy?
  - We had a write-back cache with a write-allocate policy? (Assume 25% of all misses result in a dirty eviction)

Practice Problem 2: Memory Usage

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  - A program that generates 2 Billion loads and 1 Billion stores, each 4 bytes in size.
  - A cache with a 32-byte block which gets a 95% hit rate on that program.

- Let's start with the no-cache case.
  - All stores go to memory and are 4 bytes each
    - Writes: 1 billion stores* 4 bytes = 4 billion bytes
  - All loads go to memory and are 4 bytes each.
    - Reads: 2 billion loads* 4 bytes = 8 billion bytes
- Write-through with no write-allocate?

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- Write-though, no allocate.
  - All stores still go to memory and are still 4 bytes each.
    - Writes: 1 billion stores* 4 bytes = 4 billion bytes
  - Only loads that miss in the cache go to memory. But they read the full cache block.
    - Reads: 2 billion loads* 0.05* 32 bytes = 3.2 billion bytes

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- Write-back, write-allocate (25% of all misses result in a dirty eviction)
  - *Store* misses result in a cache block being read.
    - Reads: 1 billion stores* 0.05* 32 bytes = 1.6 billion bytes
  - *Load* misses result in a cache block being read.
    - Reads: 2 billion loads* 0.05* 32 bytes = 3.2 billion bytes
  - So that is 4.8 billion bytes of data read.

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- Say you have the following:
  - A program that generates 2 Billion loads and 1 Billion stores, each 4 bytes in size.
  - A cache with a 32-byte block which gets a 95% hit rate on that program.

- Write-back, write-allocate (25% of all misses result in a dirty eviction)
  - *Store* misses result in dirty eviction 1/4 of the time.
    - Reads: 1 billion stores* 0.05* 32 bytes*(.25) = 0.4 billion bytes
  - *Load* misses result in a cache block being read.
    - Reads: 2 billion loads* 0.05* 32 bytes*(.25) = 0.8 billion bytes

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Practice Problem 3: CPI w/ Caches 2

- Given a 200 MHz processor with 8KB instruction and data caches and a with memory access latency of 20 cycles. Both caches are 2-way associative. A program running on this processor has a 95% icache hit rate and a 90% dcache hit rate. On average, 30% of the instructions are loads or stores. The CPI of this system, if caches were ideal would be 1.
- Suppose you have 2 options for the next generation processor, which do you pick?
  - Option 1: Double the clock frequency—assume this will increase your memory latency to 40 cycles. Also assume a base CPI of 1 can still be achieved after this change.
  - Option 2: Double the size of your caches, this will increase the instruction cache hit rate to 98% and the data cache hit rate to 95%. Assume the hit latency is still 1 cycle.

Practice Problem 3: Solution

Option 1: (double clock freq, base cycle time is 5 ns, so new cycle time is 2.5 ns)

CPI = baseCPI + IcacheStallCPI + DcacheStallCPI

CPI = 1.0 + 0.05*40 + 0.3*0.1*40 = 4.2

Execution time = 4.2 * Ninstrs * 2.5ns = 10.5ns * Ninstrs

Option 2 (icache/dcache miss rates lowered to 2% and 5%)

CPI = baseCPI + IcacheStallCPI + DcacheStallCPI

CPI = 1.0 + 0.02*20 + 0.3*0.05*20 = 1.7

Execution time = 1.7 * Ninstrs * 5ns = 8.5ns * Ninstrs

Therefore, Option 2 is the better choice

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- **Practice Problem 4**

Practice Problem 4: Guess that cache!

Here is the series of address references (in hex) to a cache of size 512 bytes. You are asked to **determine the configuration of the cache**. Assume 12-bit addresses

```
0x310 – Miss
0x30f – Miss
0x510 – Miss
0x31f – Hit
0x72d – Miss
0x72f – Hit
0x320 – Miss
0x520 – Miss
0x720 - Miss
```

Block size: ?

Associativity: ?

Number of sets: ?

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Similar to homework! Here is the series of address references (in hex) to a cache of size 512 bytes. You are asked to **determine the configuration of the cache**. Assume 12-bit addresses

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0x72f – Hit
0x320 – Miss
0x520 – Miss
0x720 - Miss

<u>Determine block size</u>

First hit must be brought in by another miss

Take closest address: 0x310, so know block size must be at least 16 bytes so 0x31f brought in when 0x310 miss occurs

Now, is the block size larger? Know that 0x30f was a miss, thus 0x310 and 0x30f not in the same block. Thus, block size must be <= 16 bytes

Thus Block Size = 16 bytes

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<u>Determine associativity</u>

Assume direct mapped: 3-bit tag, 5-bit index, 4-bit offset.
If DM, 0x310 and 0x510 would both map to index 17,
Thus 0x31f could not be a hit. So, not direct mapped.

Assume 2-way associative: 4-bit tag, 4-bit index, 4-bit offset
This fixes the green accesses, and allows 0x31f to be a hit.

What about > 2-way associative?
Now we also know that 0x720 is a miss even though 3 accesses earlier 0x72f was a hit, and thus it is in the cache. The intervening 2 accesses must kick it out, 0x320 and 0x520. Both go to set 2. If the associativity was > 2, then 0x720 would be a hit. So, must conclude that cache is 2-way associative.

Lastly, <u>number of sets = 512 / (2 * 16) = 16</u>

Next time

- Completing the hierarchy: virtual memory