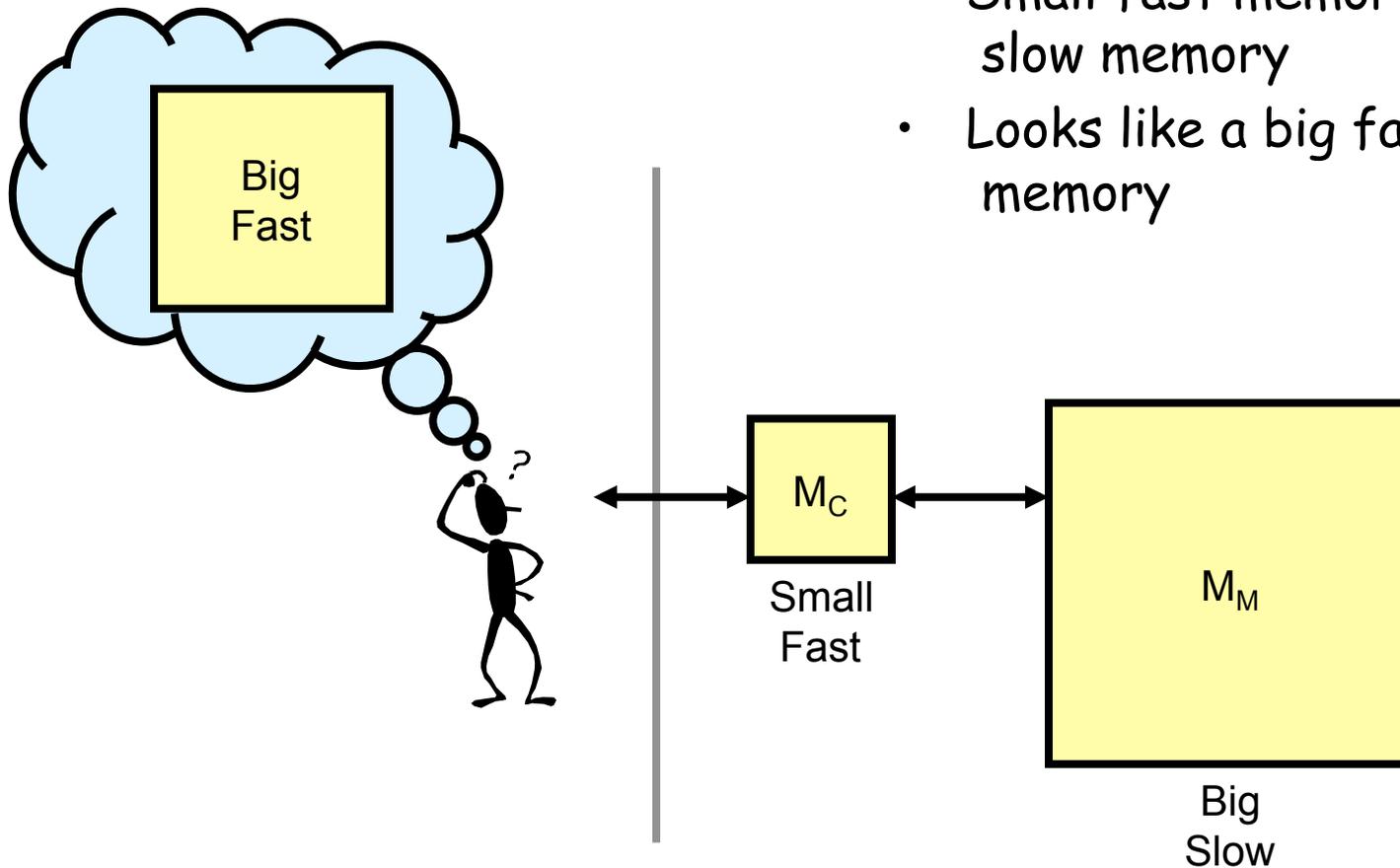
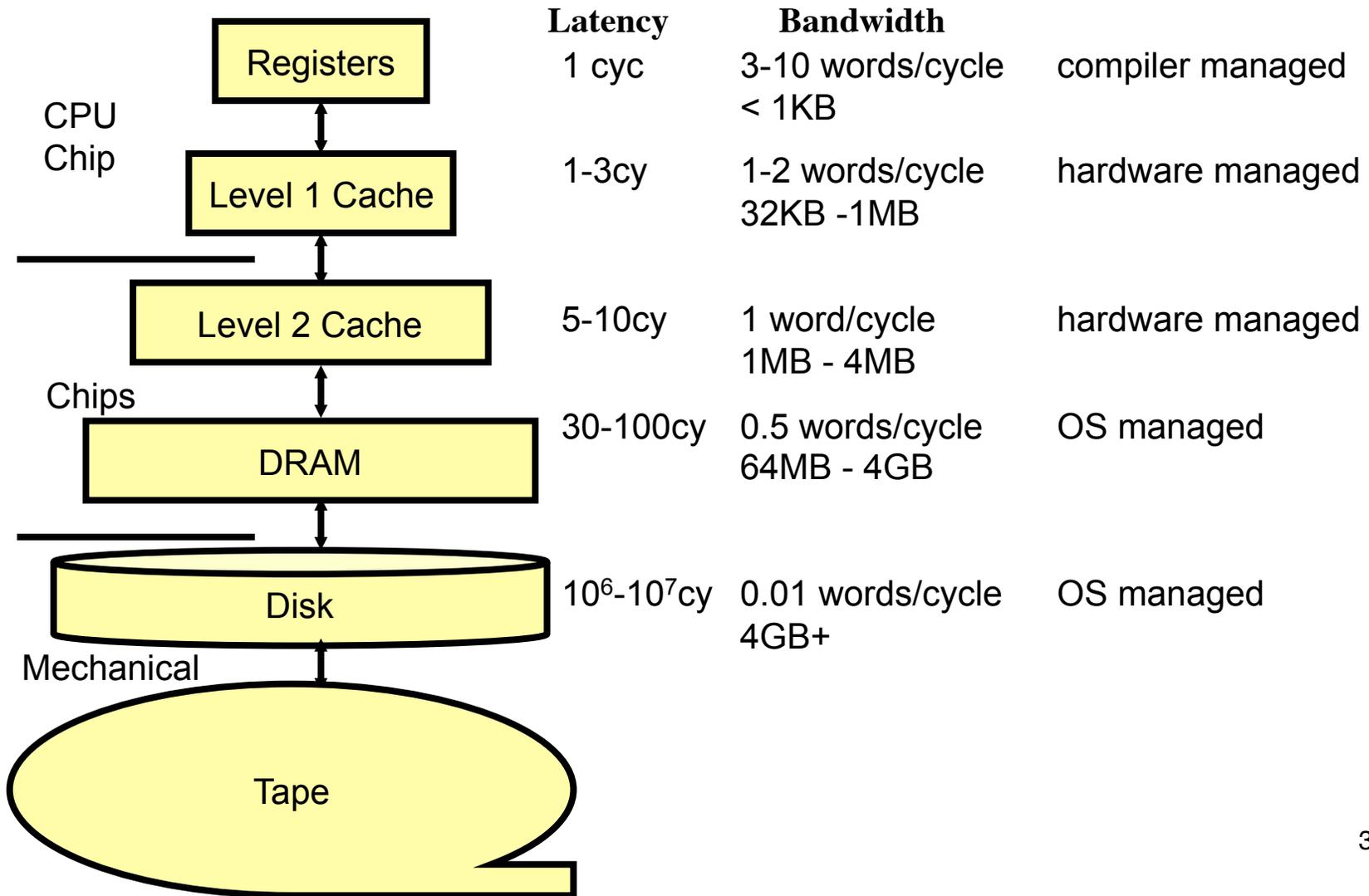


Cache Memory Theory

- Small fast memory + big slow memory
- Looks like a big fast memory



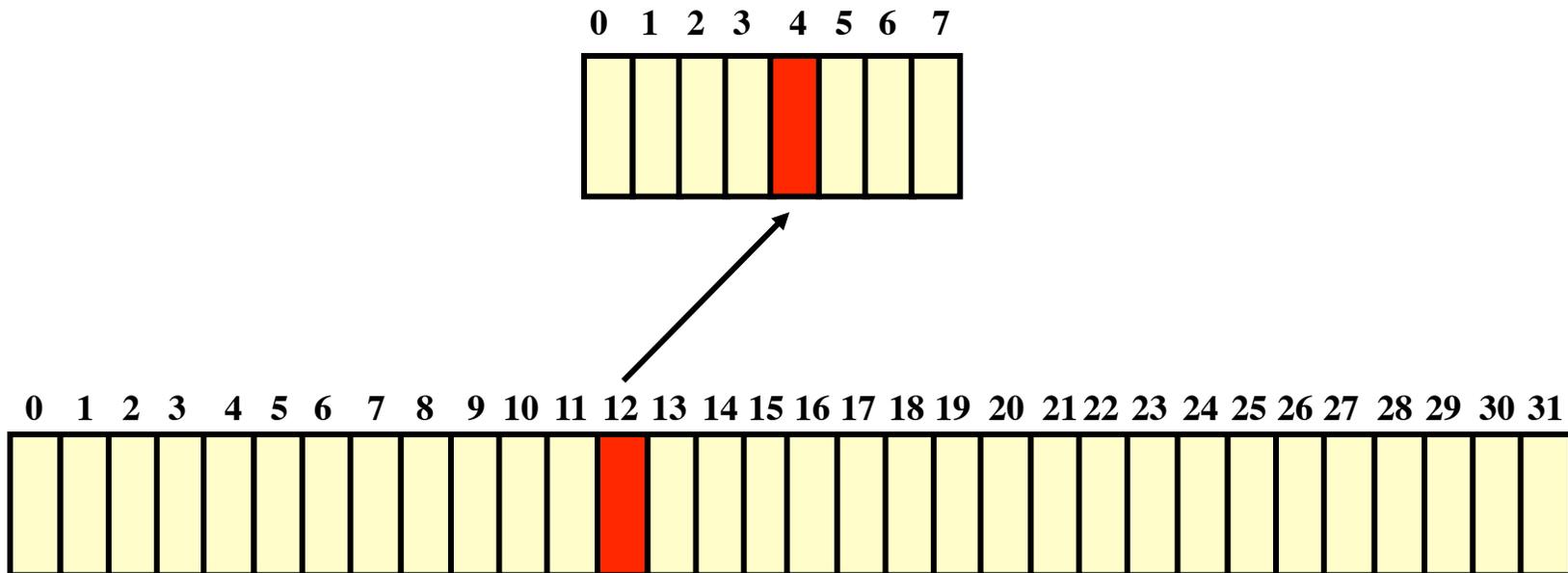
The Memory Hierarchy



Direct Mapped

- Each block mapped to exactly 1 cache location

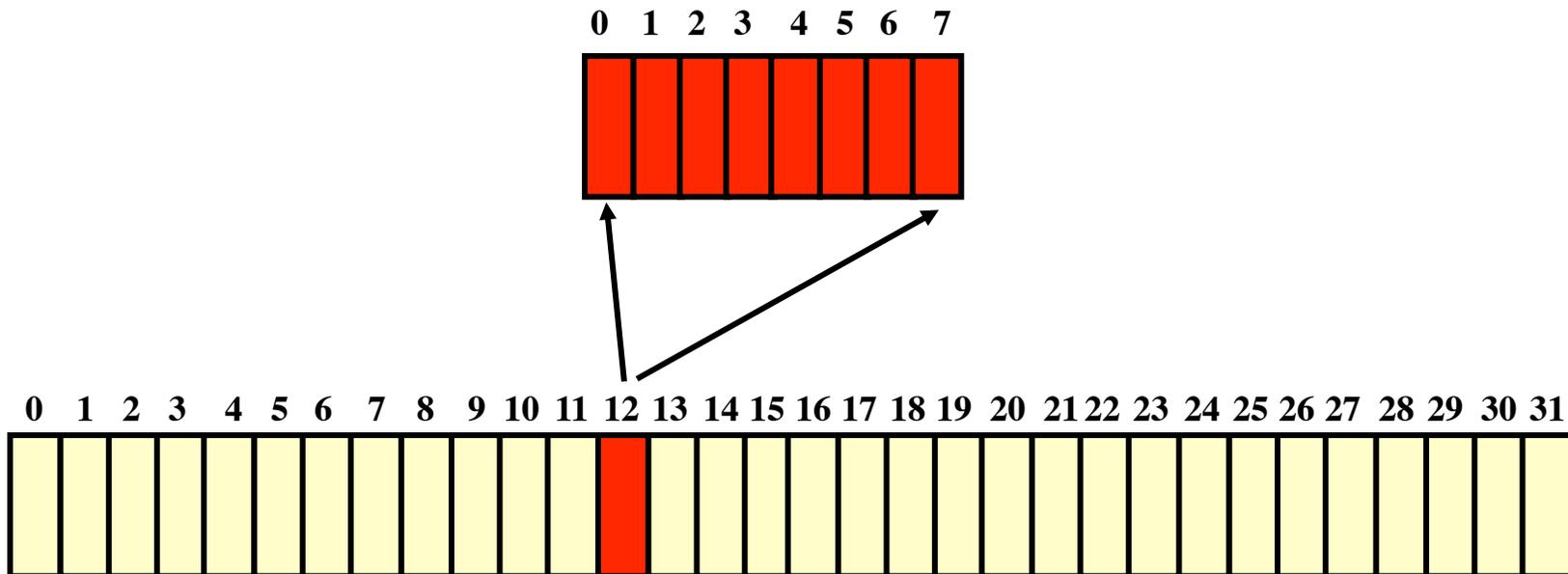
Cache location = (block address) MOD (# blocks in cache)



Fully Associative

- Each block mapped to any cache location

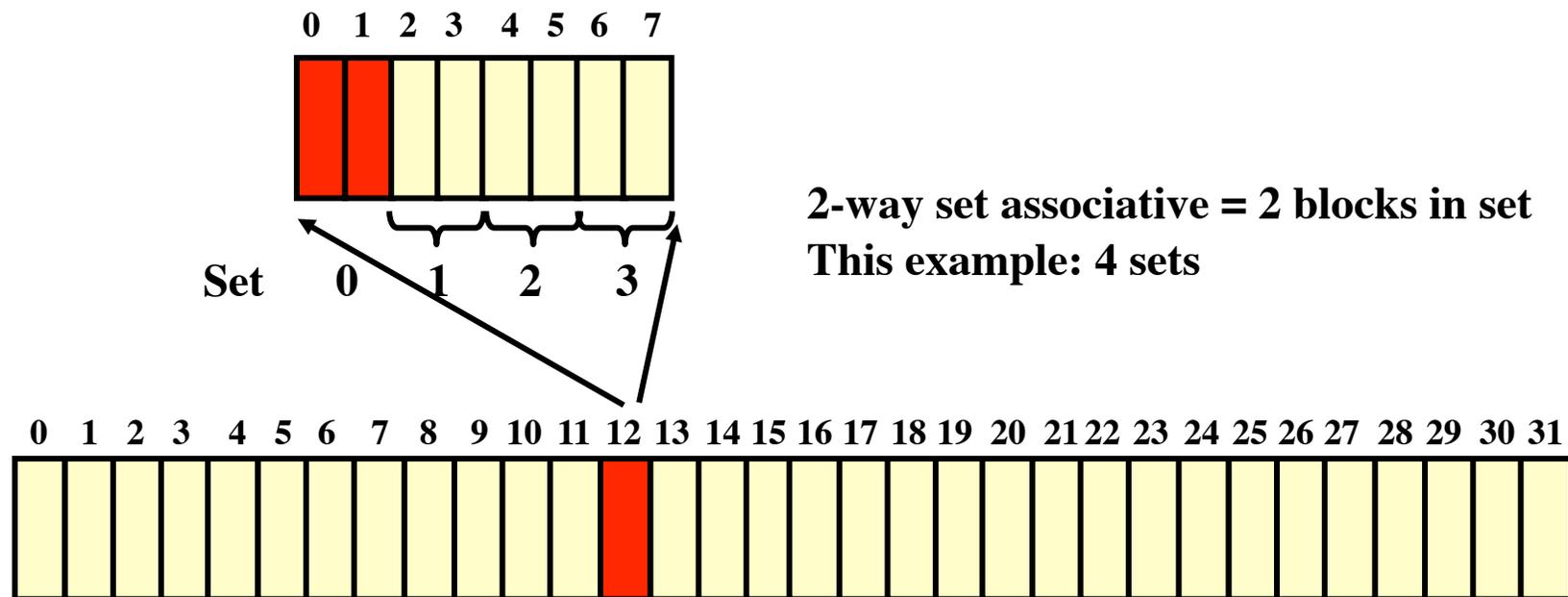
Cache location = any



Set Associative

- Each block mapped to subset of cache locations

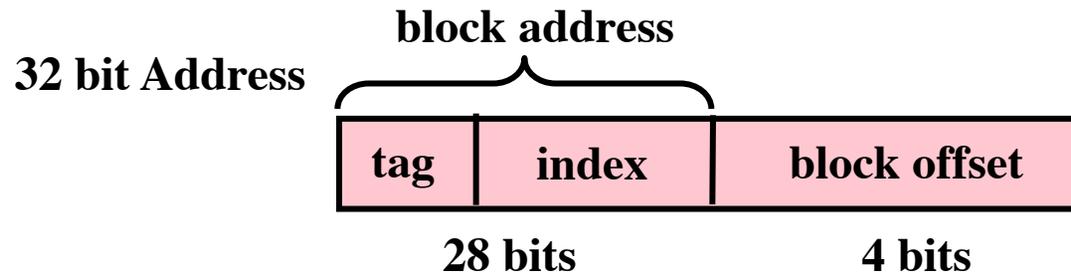
Set selection = (block address) MOD (# sets in cache)



How do we use memory address
to find block in the cache?

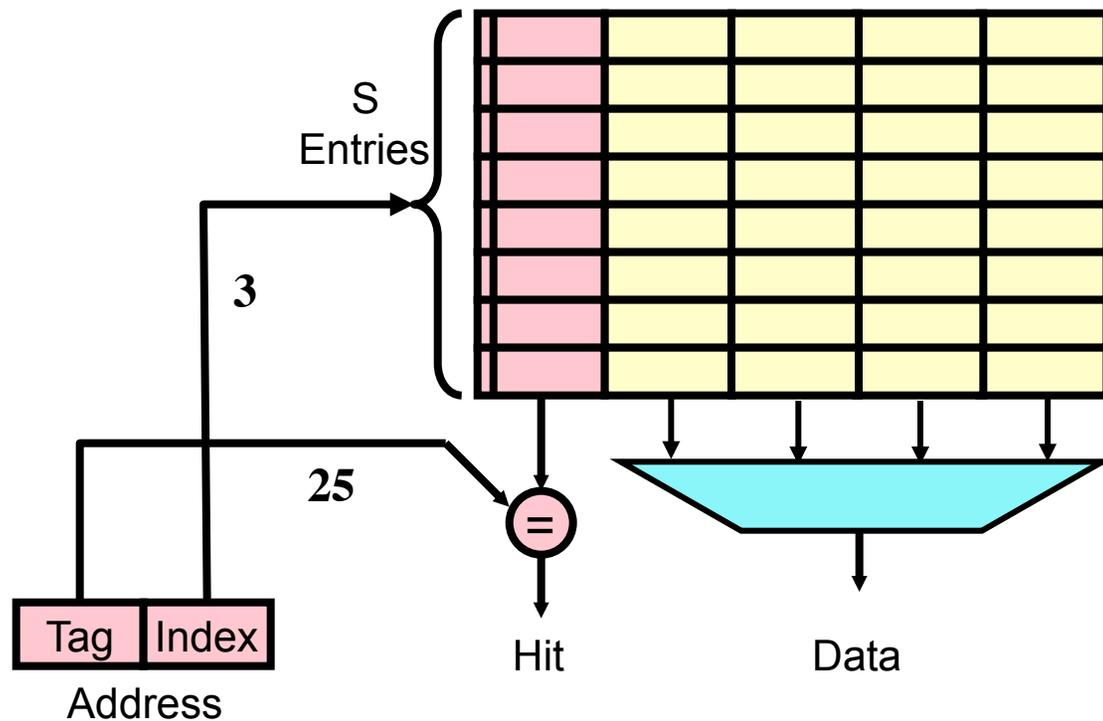
How Do We Find a Block in The Cache?

- Our Example:
 - Main memory address space = 32 bits (= 4GBytes)
 - Block size = 4 words = 16 bytes
 - Cache capacity = 8 blocks = 128 bytes



- index \Rightarrow which set
- tag \Rightarrow which data/instruction in block
- block offset \Rightarrow which word in block
- # tag/index bits determine the associativity
- tag/index bits can come from anywhere in block address

Finding a Block: Direct-Mapped



With cache capacity = 8 blocks

Finding A Block: 2-Way Set-Associative

S - sets

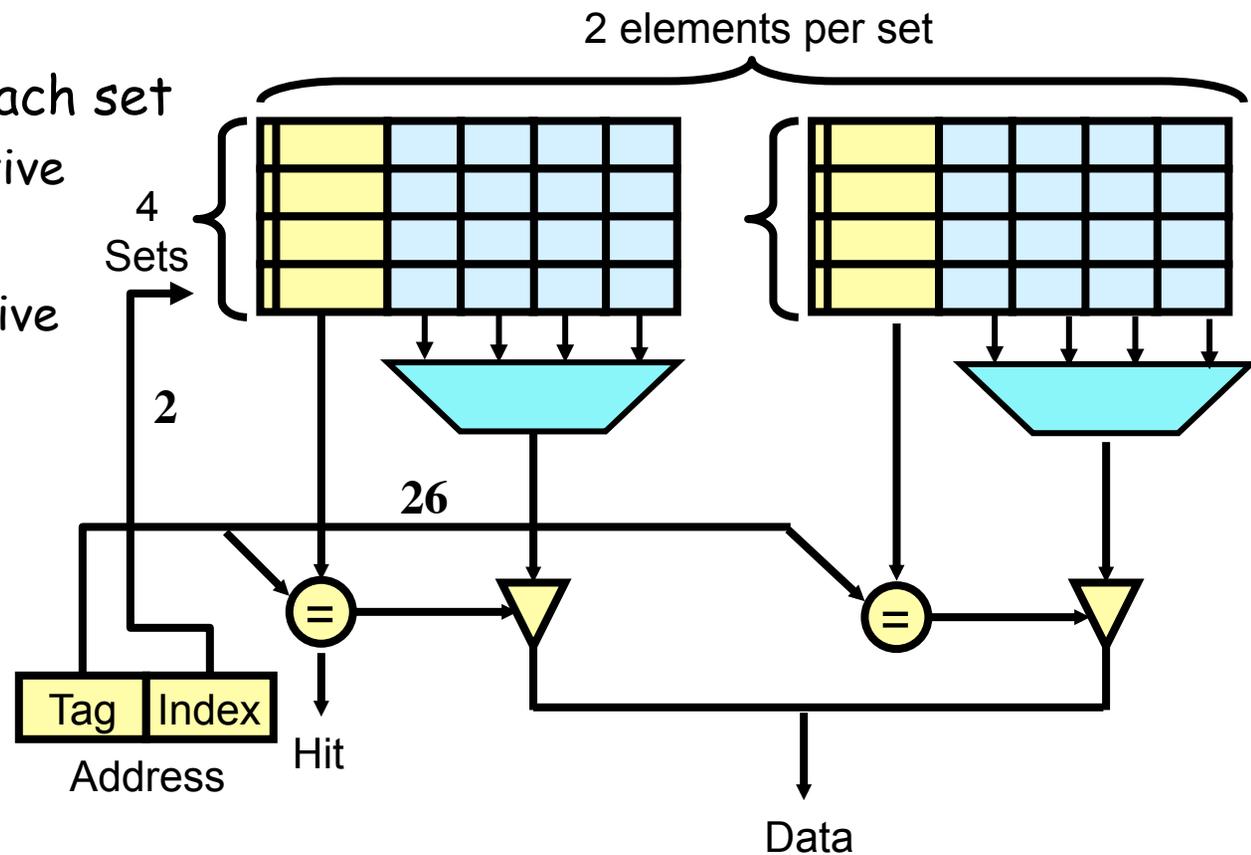
A - elements in each set

A-way associative

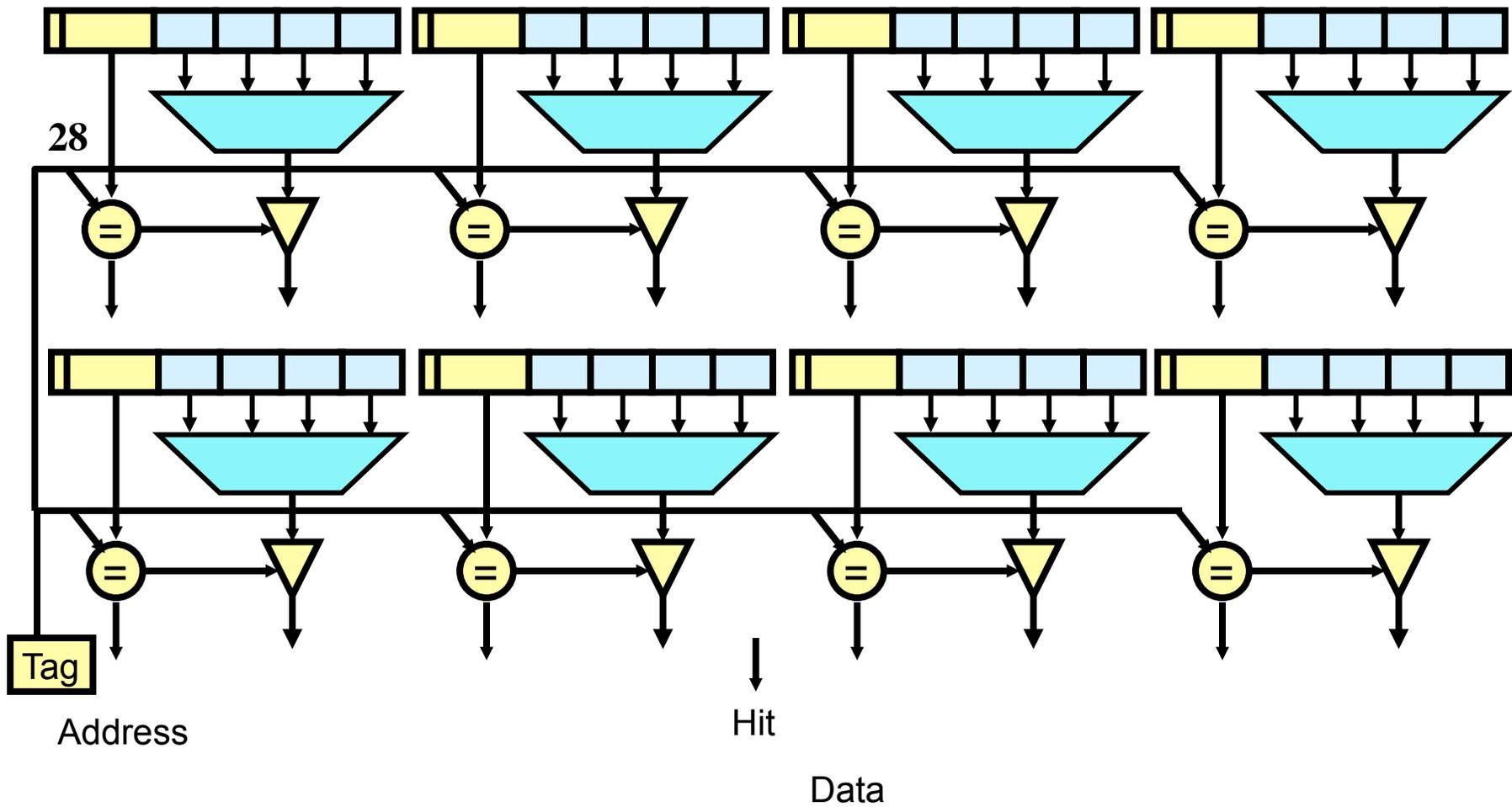
S=4, A=2

2-way associative

8-entry cache



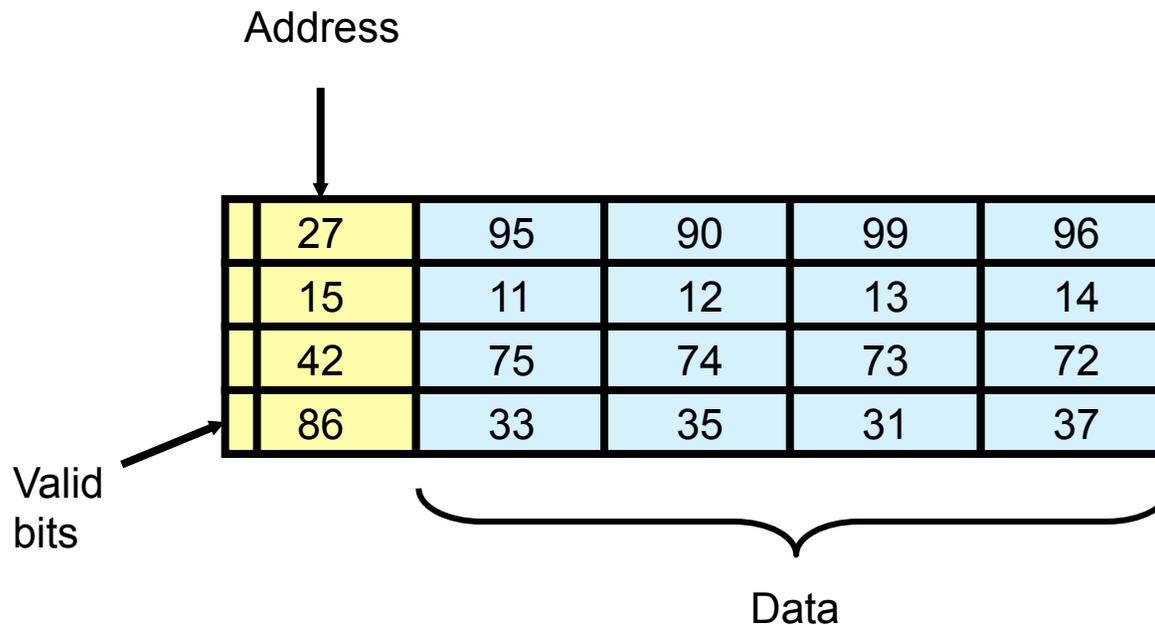
Finding A Block: Fully Associative



Set Associative Cache - cont'd

- All of main memory is divided into S sets
 - All addresses in set N map to same set of the cache
 - $\text{Addr} = N \bmod S$
 - A locations available
- Shares costly comparators across sets
- Low address bits select set
 - 2 in example
- High address bits are *tag*, used to associatively search the selected set
- Extreme cases
 - $A=1$: Direct mapped cache
 - $S=1$: Fully associative
- A need not be a power of 2

Cache Organization



- **Where does a block get placed? - DONE**
- **How do we find it? - DONE**
- **Which one do we replace when a new one is brought in?**
- **What happens on a write?**

Which Block Should Be Replaced on Miss?

- Direct Mapped
 - Choice is easy - only one option
- Associative
 - Randomly select block in set to replace
 - Least-Recently used (LRU)
- Implementing LRU
 - 2-way set-associative
 - >2 way set-associative

What Happens on a Store?

- Need to keep cache consistent with main memory
 - Reads are easy - no modifications
 - Writes are harder - when do we update main memory?
- Write-Through
 - On cache write - always update main memory as well
 - Use a write buffer to stockpile writes to main memory for speed
- Write-Back
 - On cache write - remember that block is modified (dirty bit)
 - Update main memory when dirty block is replaced
 - Sometimes need to flush cache (I/O, multiprocessing)

BUT: What if Store Causes Miss!

- Write-Allocate
 - Bring written block into cache
 - Update word in block
 - Anticipate further use of block

- No-write Allocate
 - Main memory is updated
 - Cache contents unmodified

Improving cache performance

How Do We Improve Cache Performance?

$$AMAT = t_{hit} + p_{miss} \cdot penalty_{miss}$$

How Do We Improve Cache Performance?

$$AMAT = t_{hit} + p_{miss} \cdot penalty_{miss}$$

- Reduce hit time
- Reduce miss rate
- Reduce miss penalty

Questions to think about

- As the block size goes up, what happens to the miss rate?
- ... what happens to the miss penalty?
- ... what happens to hit time?
- As the associativity goes up, what happens to the miss rate?
- ... what happens to the hit time?

Reducing Miss Rate: Increase Associativity

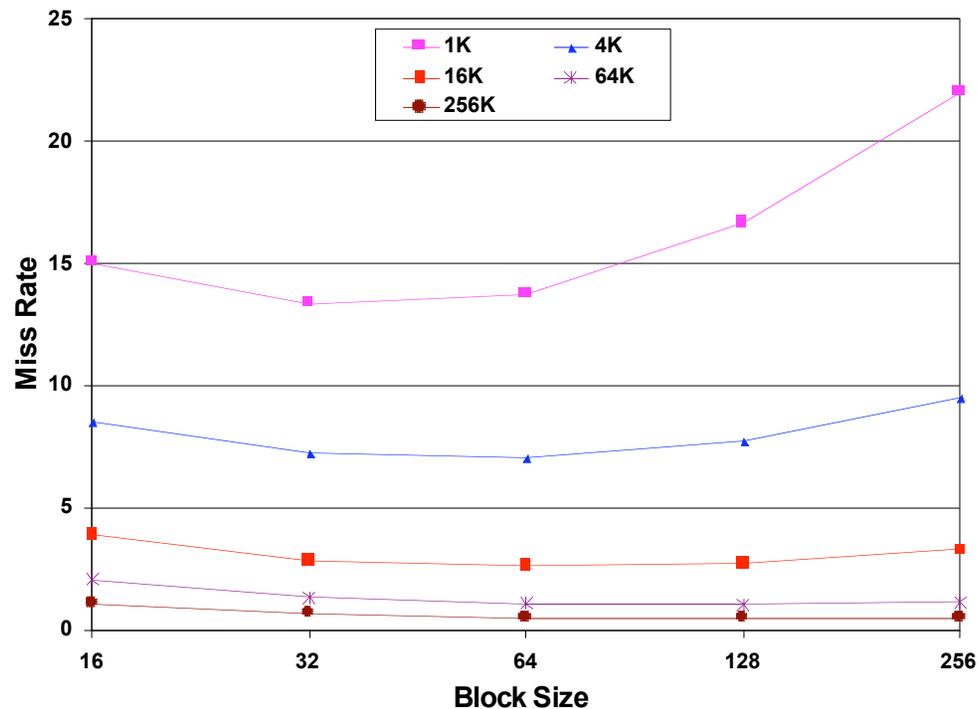
- Reduce conflict misses
- Rules of thumb
 - 8-way = fully associative
 - Direct mapped size $N = 2$ -way set associative size $N/2$
- But!
 - Size N associative is larger than Size N direct mapped
 - Associative typically slower than direct mapped (t_{hit} larger)

Reducing Hit Time

- Make Caches small and simple
 - Hit Time = 1 cycle is good (3.3ns!)
 - L1 - low associativity, relatively small
- Even L2 caches can be broken into sub-banks
 - Can exploit this for faster hit time in L2

Reducing Miss Rate: Increase Block Size

- Fetch more data with each cache miss
 - 16 bytes \Rightarrow 64, 128, 256 bytes!
 - Works because of Locality (spatial)

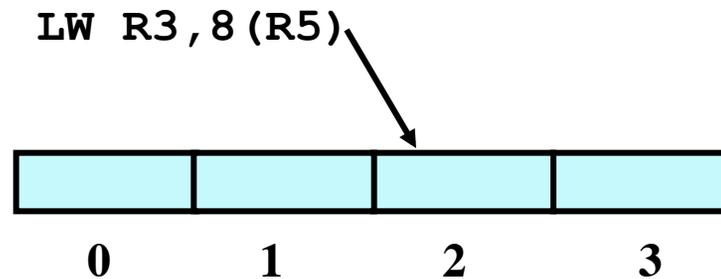


Reduce Miss Penalty: Transfer Time

- Should we transfer the whole block at once?
- Wider path to memory
 - Transfer more bytes/cycle
 - Reduces total time to transfer block
 - Limited by wires
- Two ways to do this:
 - Wider path to each memory
 - Separate paths to multiple memories
"multiple memory banks"
- Block size and transfer unit not necessarily equal!

Reduce Miss Penalty: Deliver Critical word first

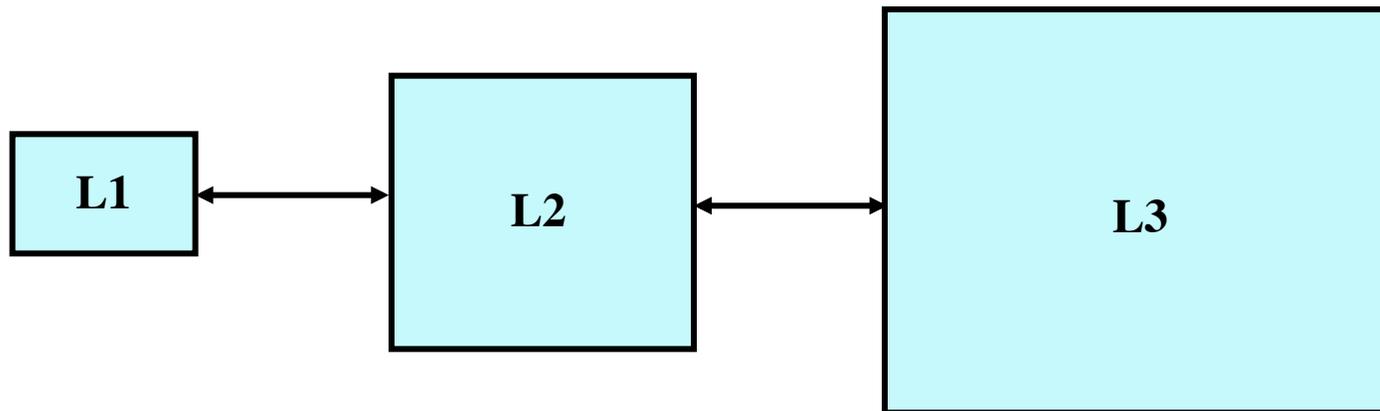
- Only need one word from block immediately



- Don't write entire word into cache first
 - Fetch word 2 first (deliver to CPU)
 - Fetch order: 2 3 0 1

Reduce Miss Penalty: More Cache Levels

- Average access time =
 $\text{HitTime}_{L1} + \text{MissRate}_{L1} * \text{MissPenalty}_{L1}$
- $\text{MissPenalty}_{L1} =$
 $\text{HitTime}_{L2} + \text{MissRate}_{L2} * \text{MissPenalty}_{L2}$
- etc.
- Size/Associativity of higher level caches?

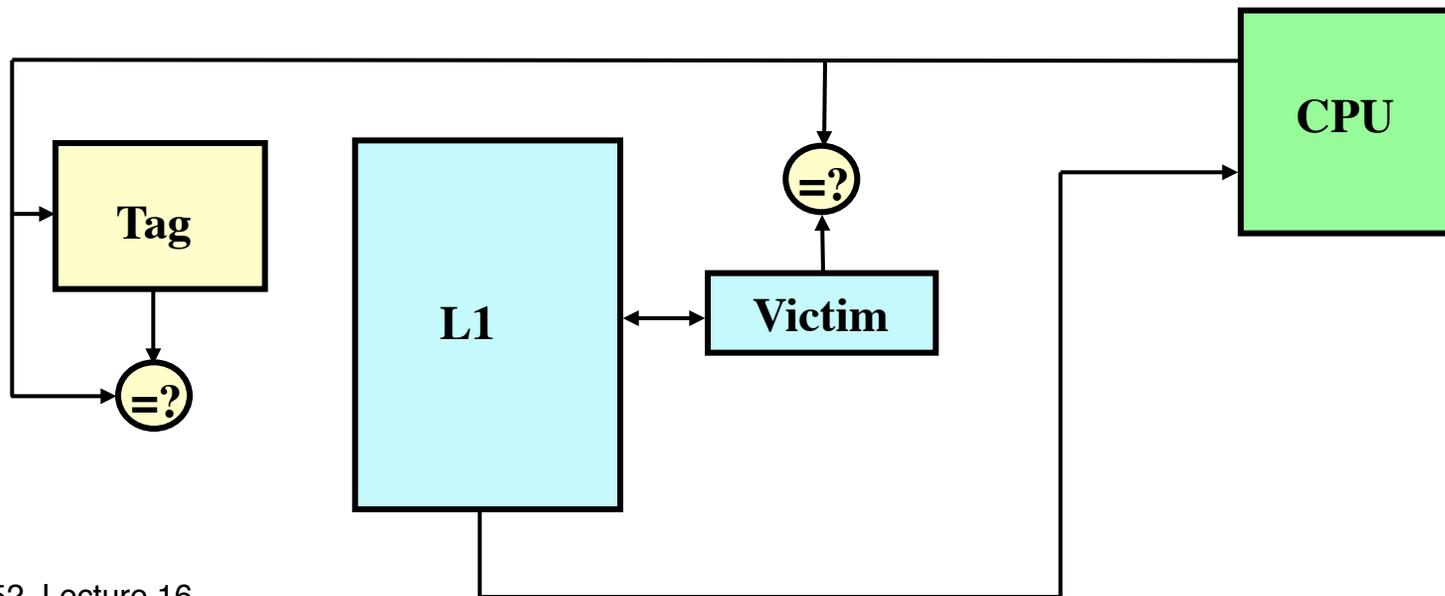


Reducing Miss Rate: Prefetching

- Fetching Data that you will probably need
- Instructions
 - Alpha 21064 on cache miss
 - Fetches requested block into instruction stream buffer
 - Fetches next sequential block into cache
- Data
 - Automatically fetch data into cache (spatial locality)
 - Issues?
- Compiler controlled prefetching
 - Inserts prefetching instructions to fetch data for later use
 - Registers or cache

Reducing Miss Rate: Use a "Victim" Cache

- Small cache (< 8 fully associative entries)
 - Jouppi 1990
 - Put evicted lines in the victim FIRST
 - Search in both the L1 and the victim cache
 - Accessed in parallel with main cache
 - Captures conflict misses



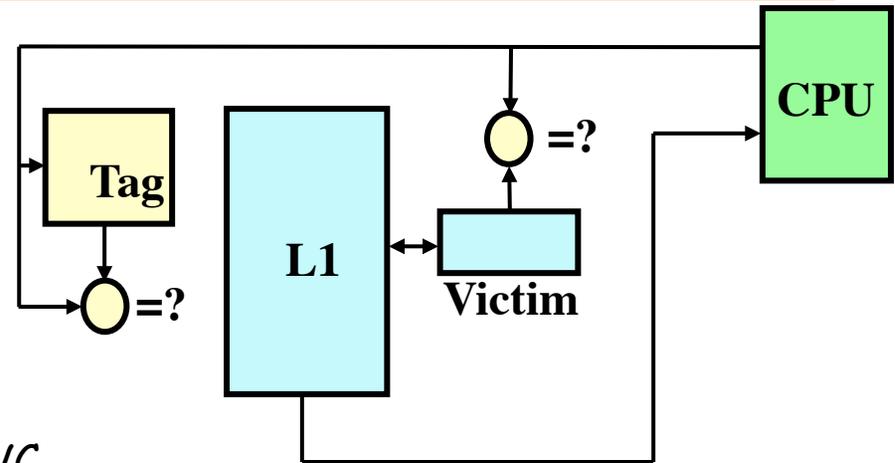
VC: Victim Cache Example

Given direct mapped L1 of 4 entries,
fully associative 1 entry VC

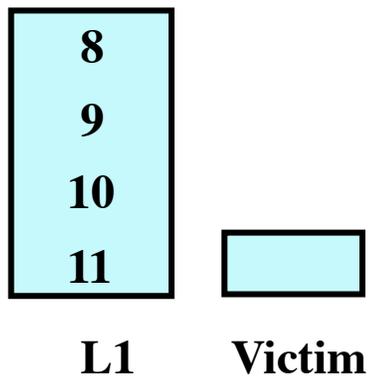
Address access sequence

- 8, 9, 10, 11, 8, 12, 9, 10, 11, 12, 8
- $\hat{\quad}$ $\hat{\quad}$ $\hat{\quad}$
 A B C

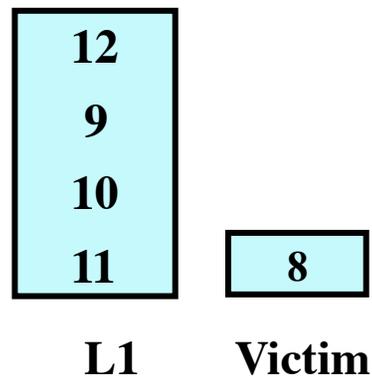
First access to 12 misses, put 8 in VC,
put 12 in L1, third access to 8 hits in VC



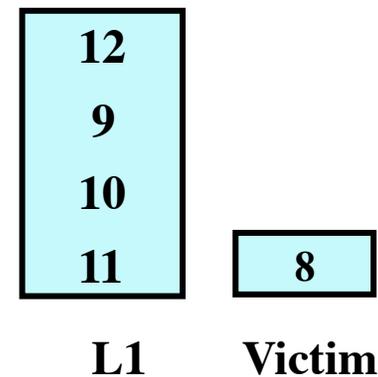
After: A



B



C



Summary

- Recap
 - Using a memory address to find location in cache
 - Deciding what to evict from the cache
 - Improving cache performance
- Next Time
 - Homework 6 is due March 25, 2010
 - Reading: P&H 5.4, 5.6

 - Virtual Memory
 - TLBs