18-447 Computer Architecture Lecture 18: Caches, Caches, Caches

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Assignment and Exam Reminders

- Lab 4: Due March 6
  - Control flow and branch prediction
- Lab 5: Due March 22
  - Data cache
- HW 4: March 18
- Exam: March 20
- Advice: Finish the labs early
  - You have almost a month for Lab 5
- Advice: Manage your time well

Agenda for the Rest of 447

- The memory hierarchy
- Caches, caches, more caches (high locality, high bandwidth)
- Virtualizing the memory hierarchy
- Main memory: DRAM
- Main memory control, scheduling
- Memory latency tolerance techniques
- Non-volatile memory

- Multiprocessors
- Coherence and consistency
- Interconnection networks
- Multi-core issues

Readings for Today and Next Lecture

- Memory Hierarchy and Caches

Required

- Cache chapters from P&H: 5.1-5.3
- Memory/cache chapters from Hamacher+: 8.1-8.7

Required + Review:

- Wilkes, "Slave Memories and Dynamic Storage Allocation," IEEE Trans. On Electronic Computers, 1965.
- Qureshi et al., "A Case for MLP-Aware Cache Replacement,“ ISCA 2006.

Review: Caching Basics

- Caches are structures that exploit locality of reference in memory
  - Temporal locality
  - Spatial locality

- They can be constructed in many ways
  - Can exploit either temporal or spatial locality or both

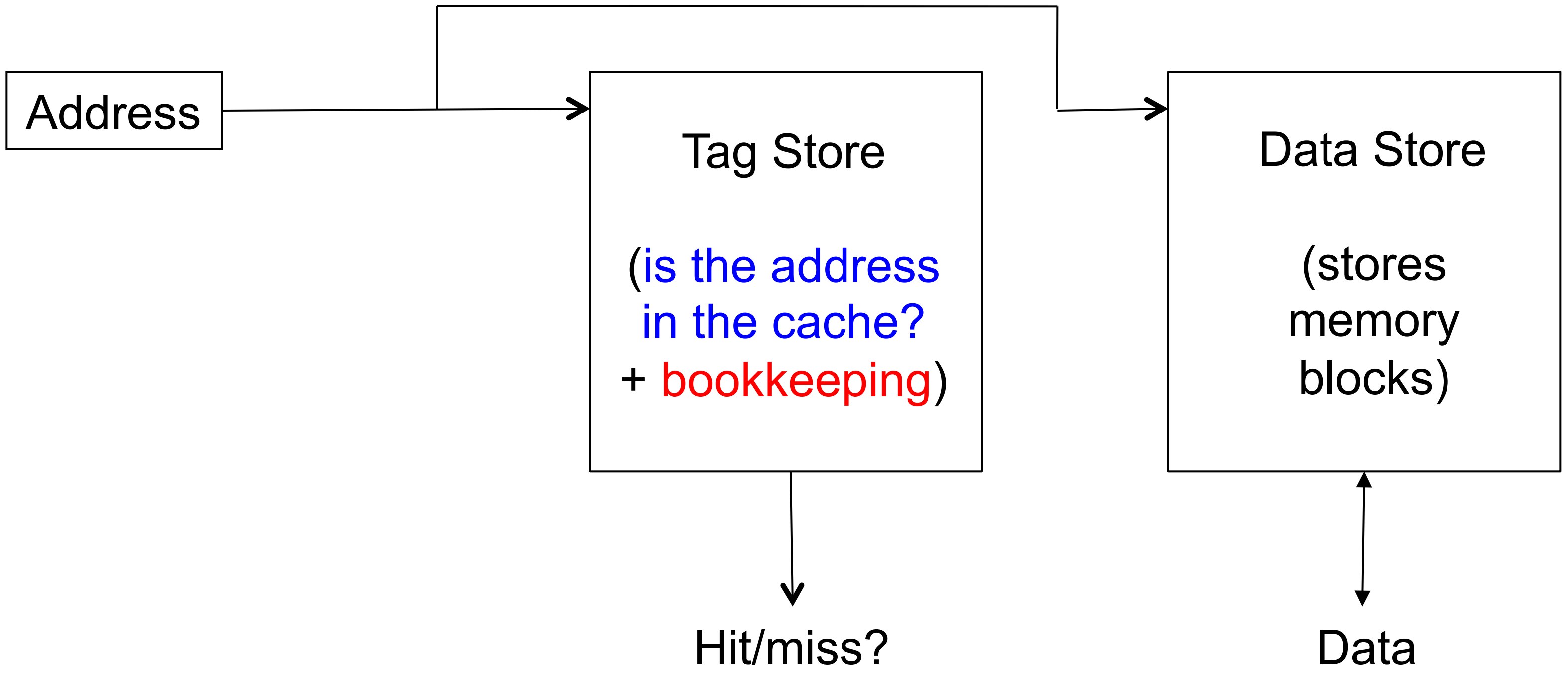
Review: Caching Basics

- Block (line): Unit of storage in the cache
  - Memory is logically divided into cache blocks that map to locations in the cache

- When data referenced
  - HIT: If in cache, use cached data instead of accessing memory
  - MISS: If not in cache, bring block into cache
    - Maybe have to kick something else out to do it

- Some important cache design decisions
  - Placement: where and how to place/find a block in cache?
  - Replacement: what data to remove to make room in cache?
  - Granularity of management: large, small, uniform blocks?
  - Write policy: what do we do about writes?
  - Instructions/data: Do we treat them separately?

Cache Abstraction and Metrics



- Cache hit rate = (# hits) / (# hits + # misses) = (# hits) / (# accesses)
- Average memory access time (AMAT)
  = (hit-rate * hit-latency) + (miss-rate * miss-latency)
- Aside: *Can reducing AMAT reduce performance?*

A Basic Hardware Cache Design

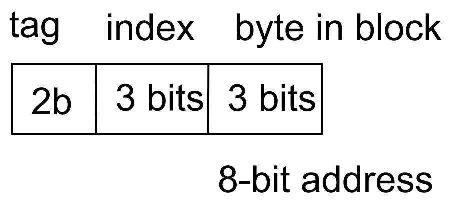
- We will start with a basic hardware cache design

- Then, we will examine a multitude of ideas to make it better

Blocks and Addressing the Cache

- Memory is logically divided into fixed-size blocks

- Each block maps to a location in the cache, determined by the index bits in the address
  - used to index into the tag and data stores



- Cache access:

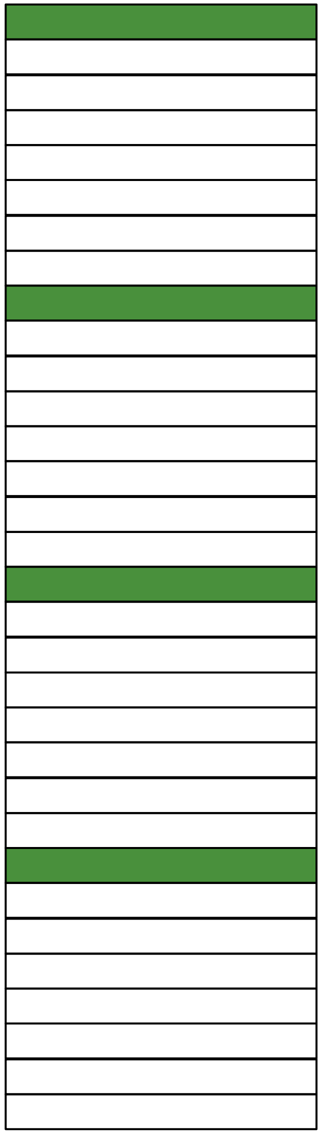
  1) index into the tag and data stores with index bits in address

  2) check valid bit in tag store

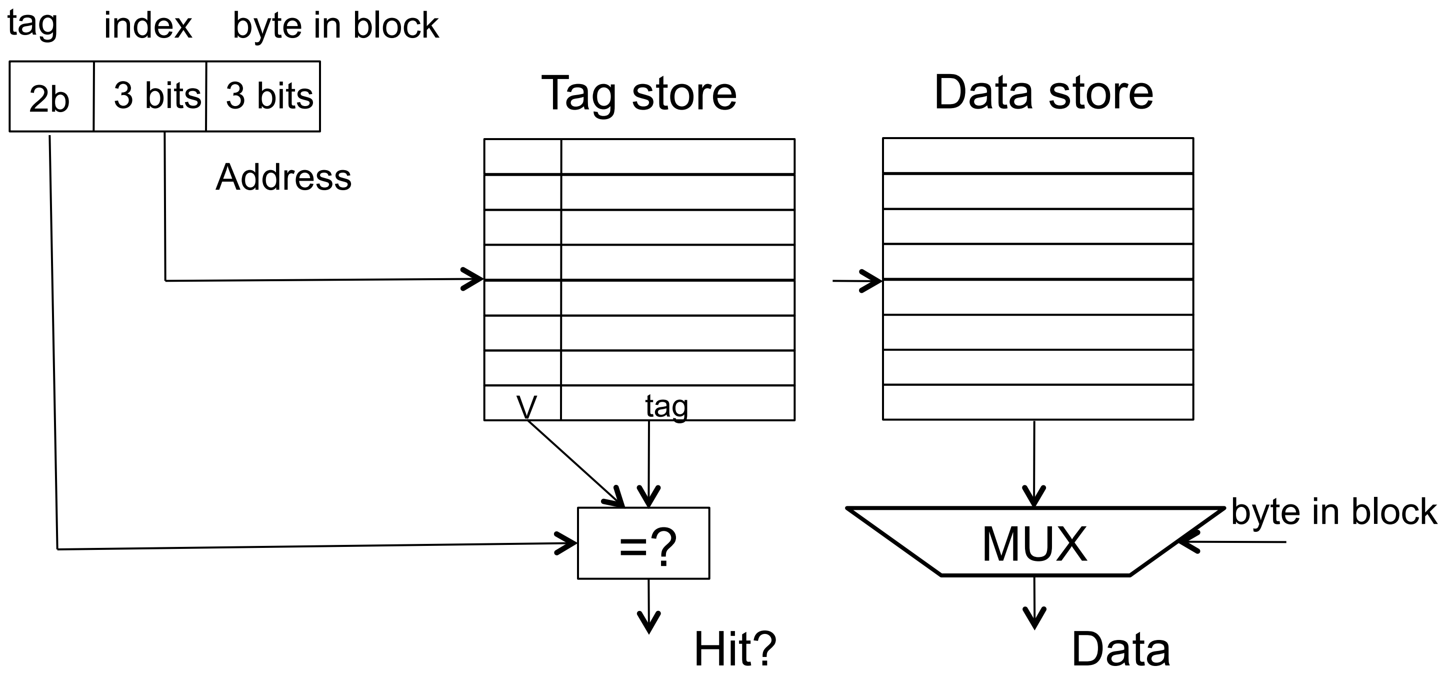
  3) compare tag bits in address with the stored tag in tag store

- If a block is in the cache (cache hit), the stored tag should be valid and match the tag of the block

Direct-Mapped Cache: Placement and Access



- Assume byte-addressable memory: 256 bytes, 8-byte blocks → 32 blocks
- Assume cache: 64 bytes, 8 blocks
  - Direct-mapped: A block can go to only one location



  - Addresses with same index contend for the same location
    - Cause conflict misses

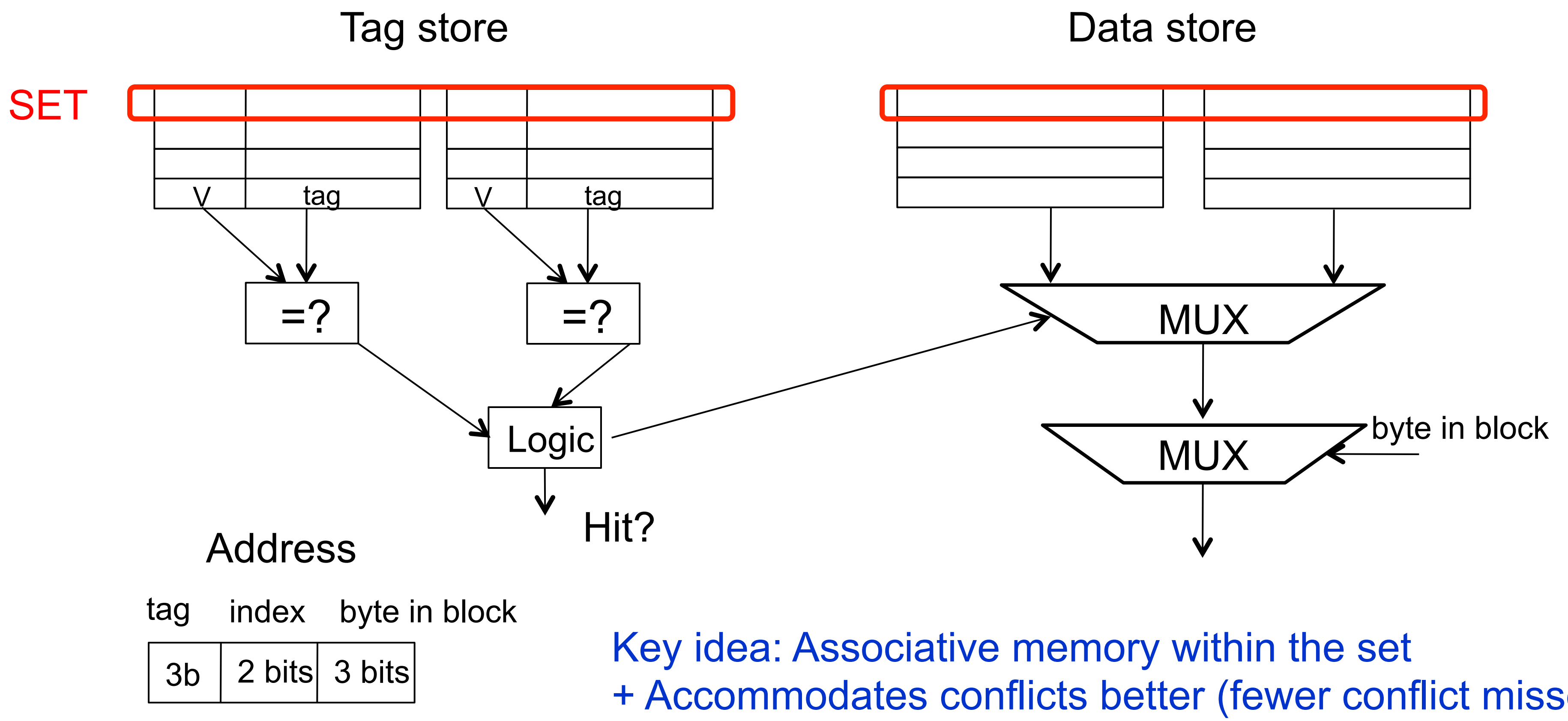
Direct-Mapped Caches

- Direct-mapped cache: Two blocks in memory that map to the same index in the cache cannot be present in the cache at the same time
  - One index → one entry

- Can lead to 0% hit rate if more than one block accessed in an interleaved manner map to the same index
  - Assume addresses A and B have the same index bits but different tag bits
  - A, B, A, B, A, B, A, B, … → conflict in the cache index
  - All accesses are conflict misses

Set Associativity

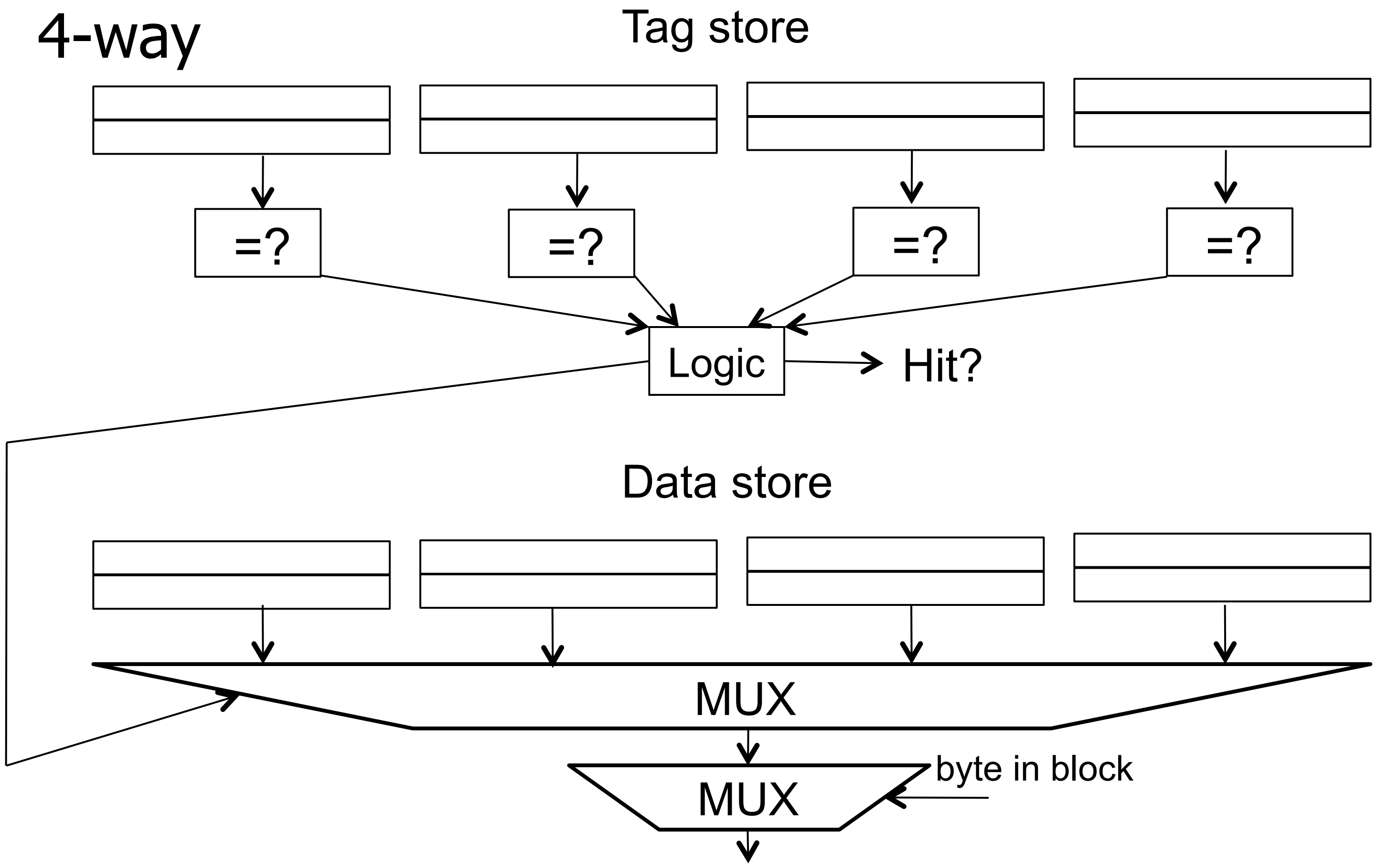
- Addresses 0 and 8 always conflict in direct mapped cache
- Instead of having one column of 8, have 2 columns of 4 blocks



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

Higher Associativity

- 4-way

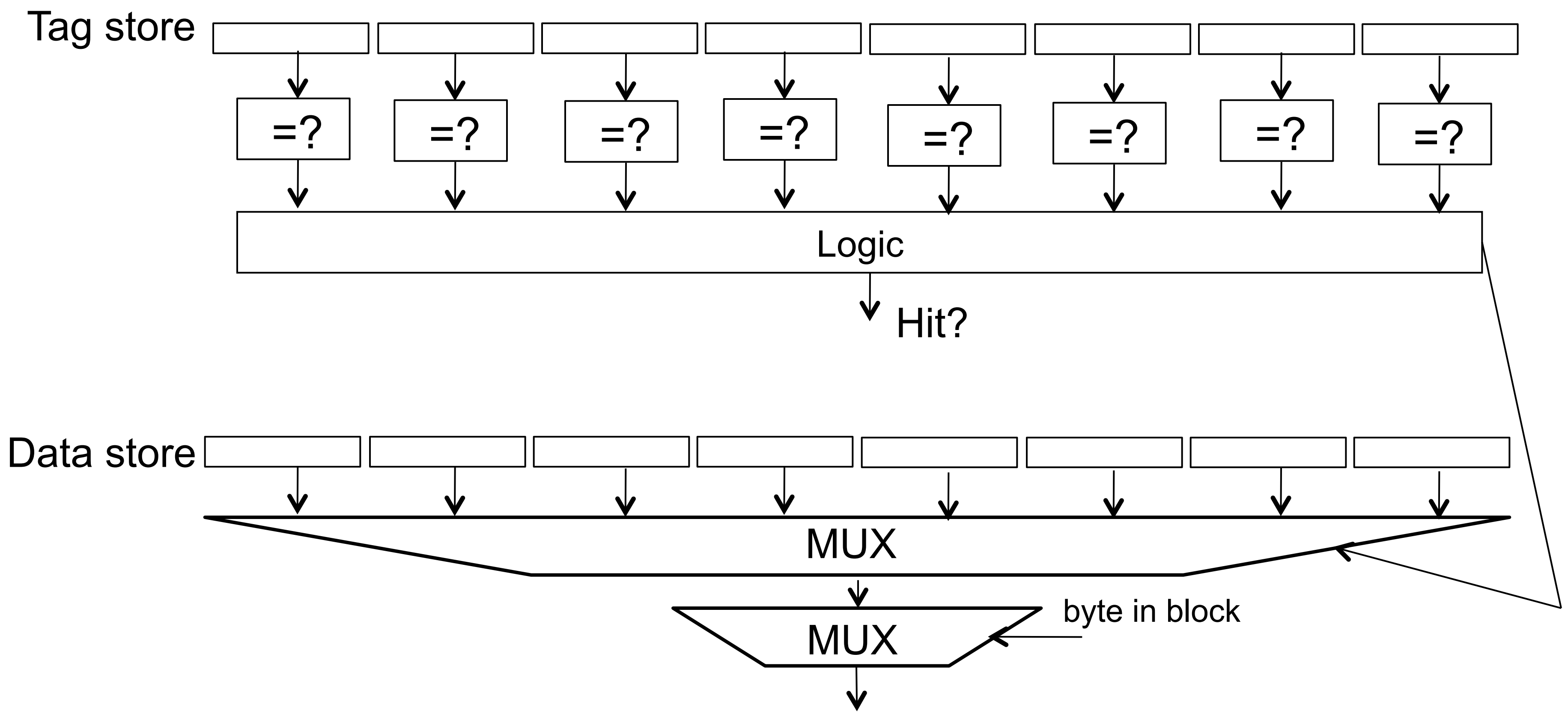


+ Likelihood of conflict misses even lower

-- More tag comparators and wider data mux; larger tags

Full Associativity

- Fully associative cache
  - A block can be placed in any cache location



Associativity (and Tradeoffs)

- Degree of associativity: How many blocks can map to the same index (or set)?

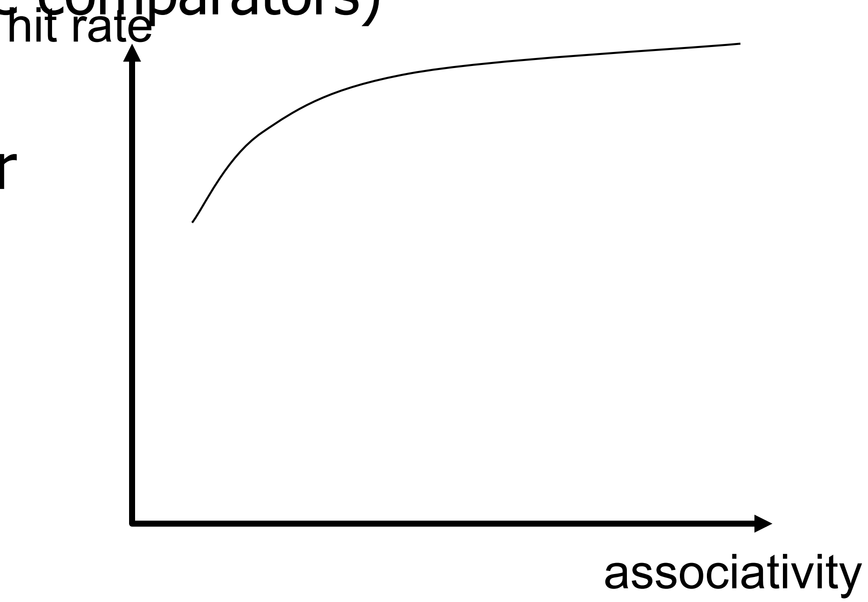
- Higher associativity

  ++ Higher hit rate

  -- Slower cache access time (hit latency and data access latency)

  -- More expensive hardware (more comparators)

- Diminishing returns from higher associativity



Issues in Set-Associative Caches

- Think of each block in a set having a "priority"
  - Indicating how important it is to keep the block in the cache
- Key issue: How do you determine/adjust block priorities?
- There are three key decisions in a set:
  - Insertion, promotion, eviction (replacement)

- Insertion: What happens to priorities on a cache fill?
  - Where to insert the incoming block, whether or not to insert the block
- Promotion: What happens to priorities on a cache hit?
  - Whether and how to change block priority
- Eviction/replacement: What happens to priorities on a cache miss?
  - Which block to evict and how to adjust priorities

Eviction/Replacement Policy

- Which block in the set to replace on a cache miss?
  - Any invalid block first
  - If all are valid, consult the replacement policy
    - Random
    - FIFO
    - Least recently used (how to implement?)
    - Not most recently used
    - Least frequently used?
    - Least costly to re-fetch?
      - Why would memory accesses have different cost?
    - Hybrid replacement policies
    - Optimal replacement policy?

Implementing LRU

- Idea: Evict the least recently accessed block
- Problem: Need to keep track of access ordering of blocks

- Question: 2-way set associative cache:
  - What do you need to implement LRU perfectly?

- Question: 4-way set associative cache:
  - What do you need to implement LRU perfectly?
  - How many different orderings possible for the 4 blocks in the set?
  - How many bits needed to encode the LRU order of a block?
  - What is the logic needed to determine the LRU victim?

Approximations of LRU

- Most modern processors do not implement "true LRU" (also called "perfect LRU") in highly-associative caches

- Why?
  - True LRU is complex
  - LRU is an approximation to predict locality anyway (i.e., not the best possible cache management policy)

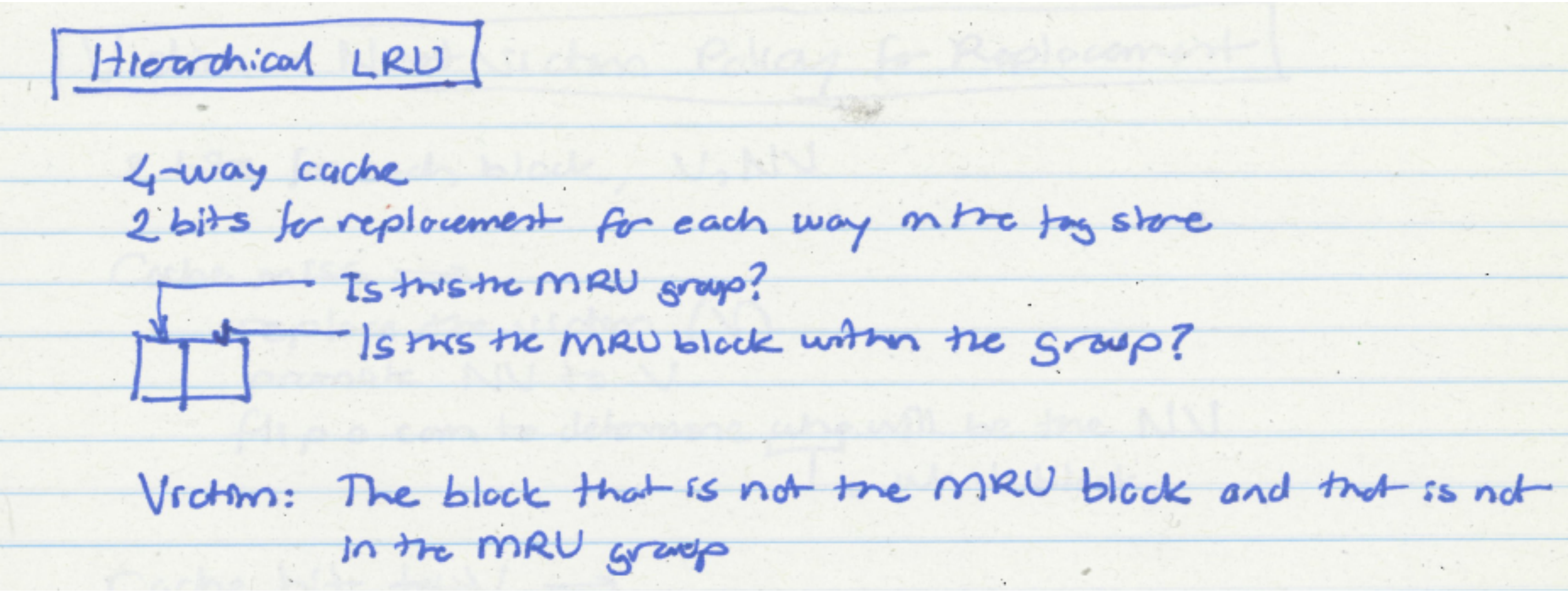
- Examples:
  - Not MRU (not most recently used)
  - Hierarchical LRU: divide the 4-way set into 2-way "groups", track the MRU group and the MRU way in each group
  - Victim-NextVictim Replacement: Only keep track of the victim and the next victim

Hierarchical LRU (not MRU)

- Divide a set into multiple groups
- Keep track of *only* the MRU group
- Keep track of *only* the MRU block in each group

- On replacement, select victim as:
  - A not-MRU block in one of the not-MRU groups (randomly pick one of such blocks/groups)

Hierarchical LRU (not MRU) Example



Hierarchical LRU

4-way cache

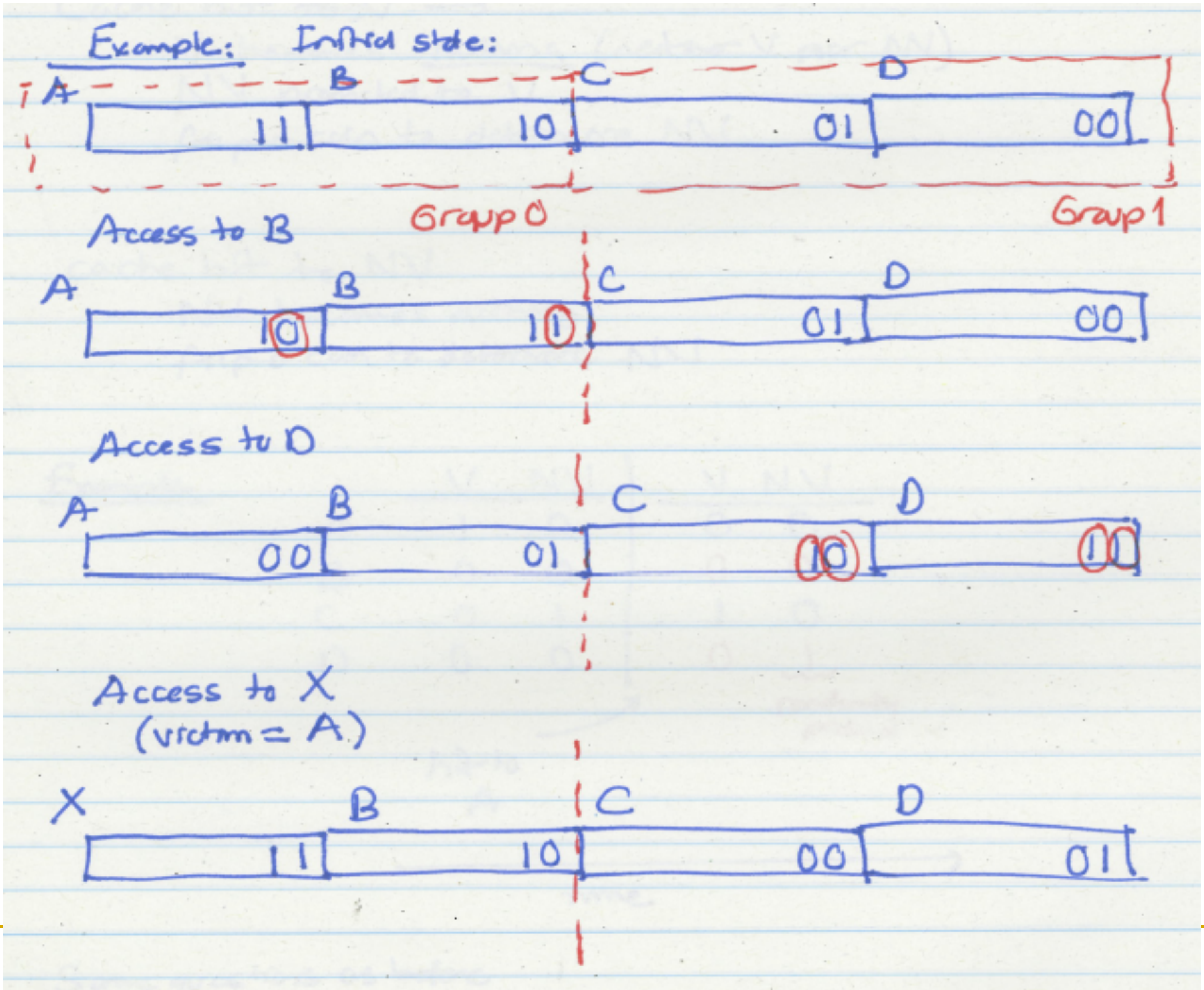
2 bits for replacement for each way in the tag store

Is this the MRU group?

Is this the MRU block within the group?

Victim: The block that is not the MRU block and that is not in the MRU group

Hierarchical LRU (not MRU) Example



Hierarchical LRU (not MRU): Questions

- 16-way cache
- 2 8-way groups

- What is an access pattern that performs worse than true LRU?

- What is an access pattern that performs better than true LRU?

Victim/Next-Victim Policy

- Only 2 blocks’ status tracked in each set:
  - victim (V), next victim (NV)
  - all other blocks denoted as (O) – Ordinary block

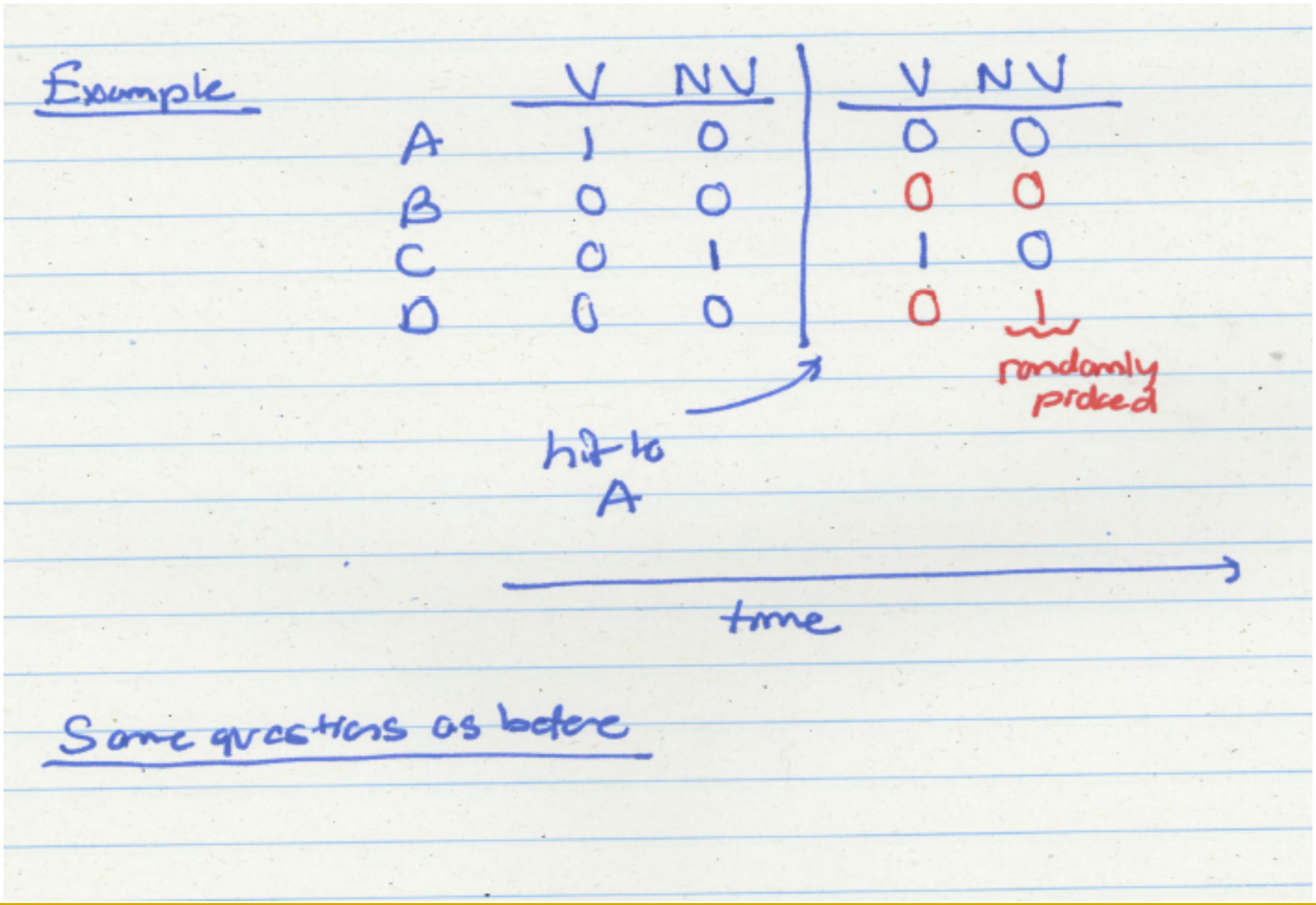
- On a cache miss
  - Replace V
  - Demote NV to V
  - Randomly pick an O block as NV

- On a cache hit to V
  - Demote NV to V
  - Randomly pick an O block as NV
  - Turn V to O

Victim/Next-Victim Policy (II)

- On a cache hit to NV
  - Randomly pick an O block as NV
  - Turn NV to O
- On a cache hit to O
  - Do nothing

Victim/Next-Victim Example



Example

	V	NV	V	NV
A	1	0	0	0
B	0	0	0	0
C	0	1	1	0
D	0	0	0	1

randomly picked

hit to A

time

Same questions as before

Cache Replacement Policy: LRU or Random

- LRU vs. Random: Which one is better?
  - Example: 4-way cache, cyclic references to A, B, C, D, E
    - 0% hit rate with LRU policy
- Set thrashing: When the "program working set" in a set is larger than set associativity
  - Random replacement policy is better when thrashing occurs
- In practice:
  - Depends on workload
  - Average hit rate of LRU and Random are similar

- Best of both Worlds: Hybrid of LRU and Random
  - How to choose between the two? Set sampling
    - See Qureshi et al., "A Case for MLP-Aware Cache Replacement," ISCA 2006.

What Is the Optimal Replacement Policy?

- Belady’s OPT
  - Replace the block that is going to be referenced furthest in the future by the program
  - Belady, “A study of replacement algorithms for a virtual-storage computer,” IBM Systems Journal, 1966.
  - How do we implement this? Simulate?

- Is this optimal for minimizing miss rate?
- Is this optimal for minimizing execution time?
  - No. Cache miss latency/cost varies from block to block!
  - Two reasons: Remote vs. local caches and miss overlapping
  - Qureshi et al. “A Case for MLP-Aware Cache Replacement,“ ISCA 2006.

Aside: Cache versus Page Replacement

- Physical memory (DRAM) is a cache for disk
  - Usually managed by system software via the virtual memory subsystem

- Page replacement is similar to cache replacement
- Page table is the "tag store" for physical memory data store

- What is the difference?
  - Required speed of access to cache vs. physical memory
  - Number of blocks in a cache vs. physical memory
  - "Tolerable" amount of time to find a replacement candidate (disk versus memory access latency)
  - Role of hardware versus software

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 consolidate 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 lower-level caches

  -- More bandwidth intensive; no coalescing 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 consolidate 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?

- Ditto for a *portion* of the block, i.e., subblock
  - E.g., 4 bytes out of 64 bytes

Sectored Caches

- Idea: Divide a block into subblocks (or sectors)
  - Have separate valid and dirty bits for each sector
  - When is this useful? (Think writes…)

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

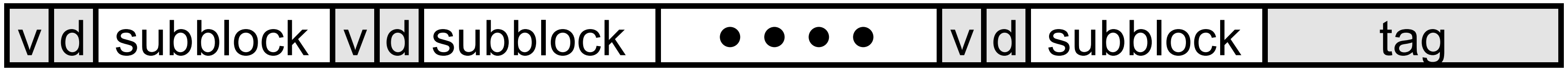
(A write simply validates and updates a subblock)

++ 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 when used for reads



Instruction vs. Data Caches

- Separate or Unified?

- Unified:

  + Dynamic sharing of cache space: no overprovisioning that might happen with static partitioning (i.e., split 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
- Second and higher levels 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
  - 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

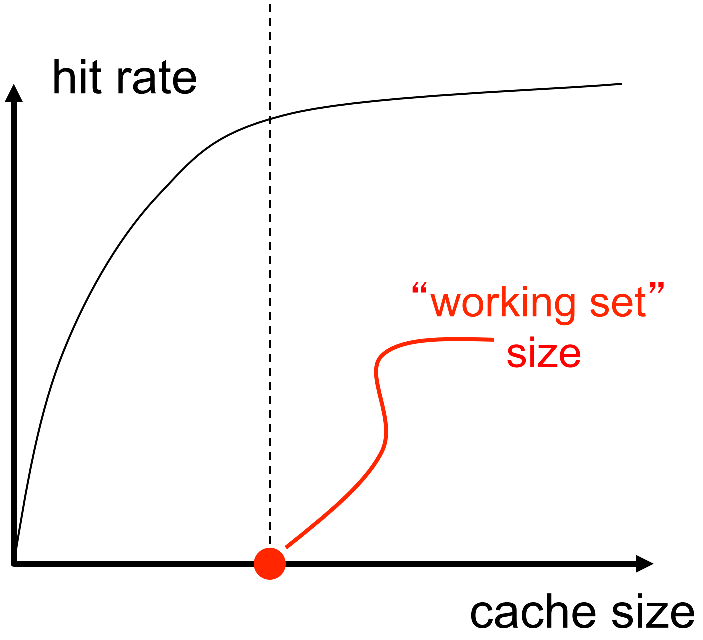
Cache Parameters vs. Miss/Hit Rate

- 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

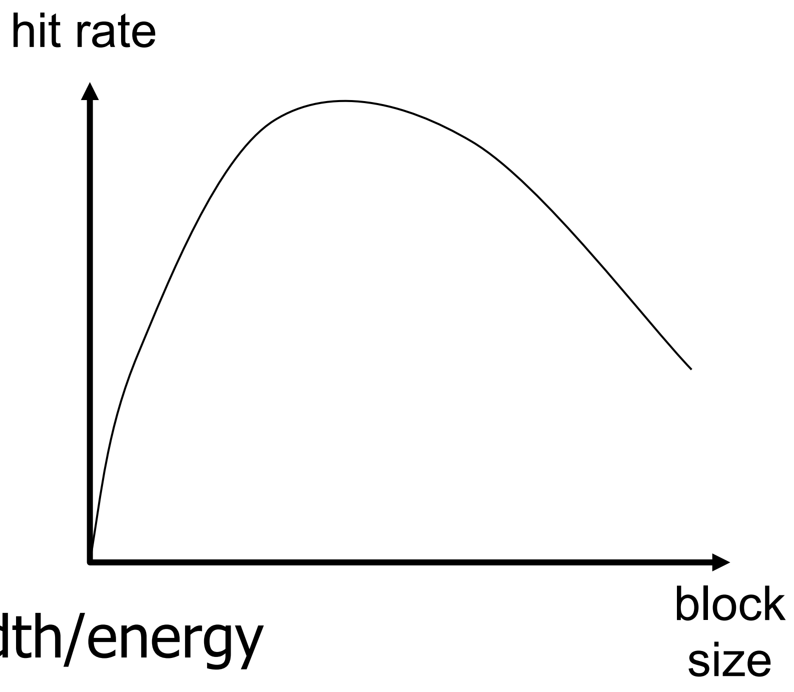


Block Size

- 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 with V bit)
      - Can improve "write" performance

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

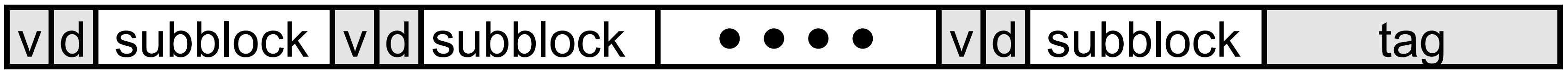
- Too large blocks
  - too few total # of blocks → less temporal locality exploitation
  - waste of cache space and bandwidth/energy if spatial locality is not high



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 bits for each subblock
  - When is this useful?



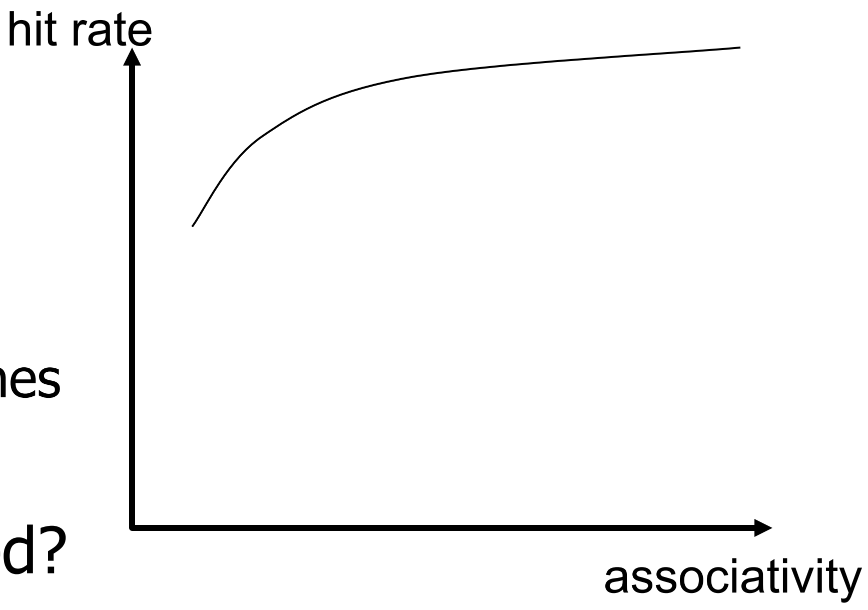
Associativity

- How many blocks can map to the same index (or set)?

- Larger associativity
  - lower miss rate, less variation among programs
  - diminishing returns, higher hit latency

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

- 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
- Conflict
  - More associativity
  - Other ways to get more associativity without making the cache associative
    - Victim cache
    - Hashing
    - Software hints?
- Capacity
  - Utilize cache space better: keep blocks that will be referenced
  - Software management: divide working set such that each "phase" fits in cache

Improving Cache "Performance"

- Remember
  - Average memory access time (AMAT)
    = (hit-rate * hit-latency) + (miss-rate * miss-latency)

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

- Reducing miss latency/cost

- Reducing hit latency/cost

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