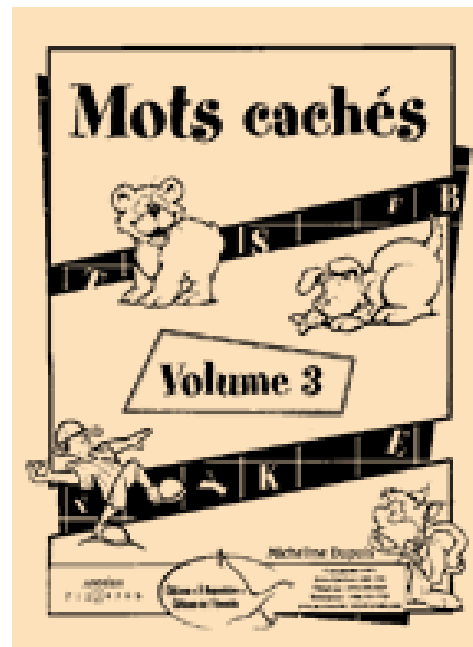


inst.eecs.berkeley.edu/~cs61c/su05
CS61C : Machine Structures

Lecture #21: Caches 3

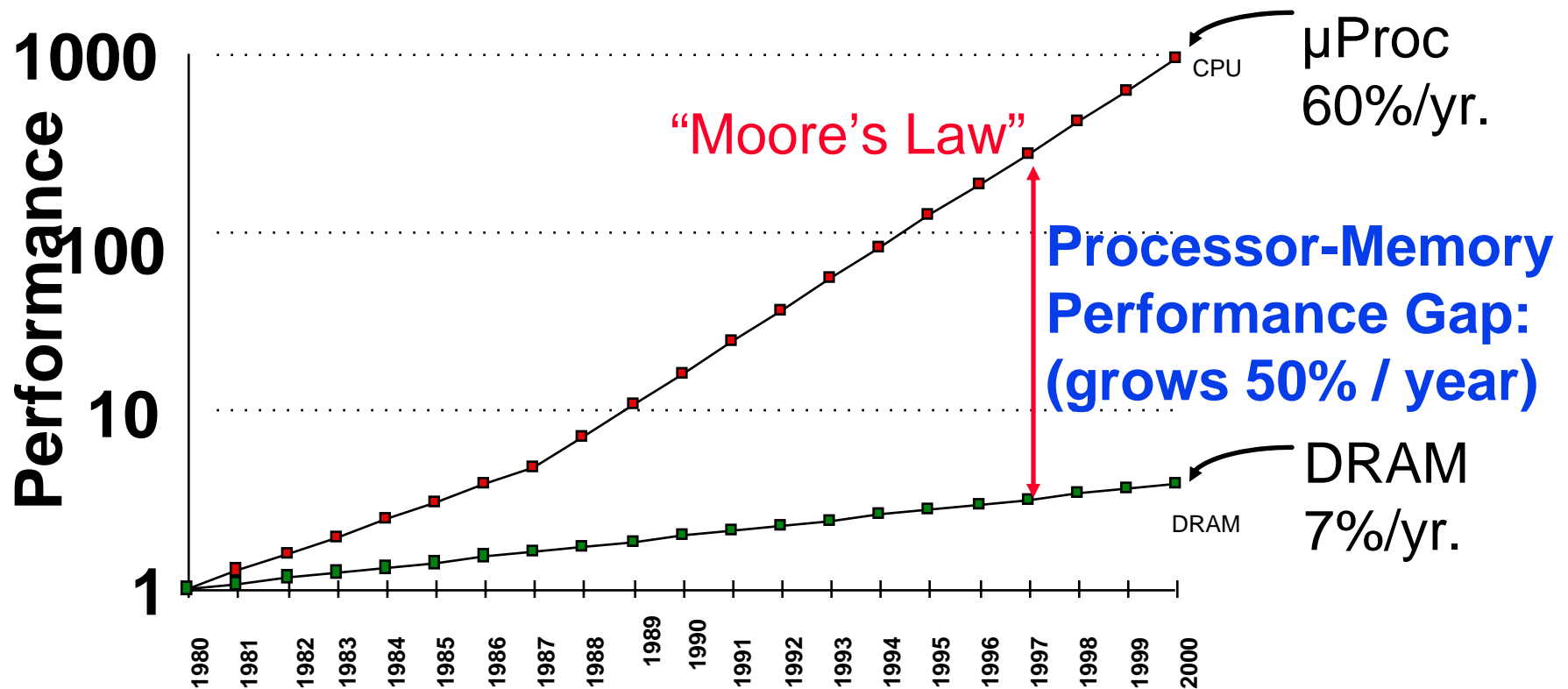


2005-07-27

Andy Carle



Review: Why We Use Caches

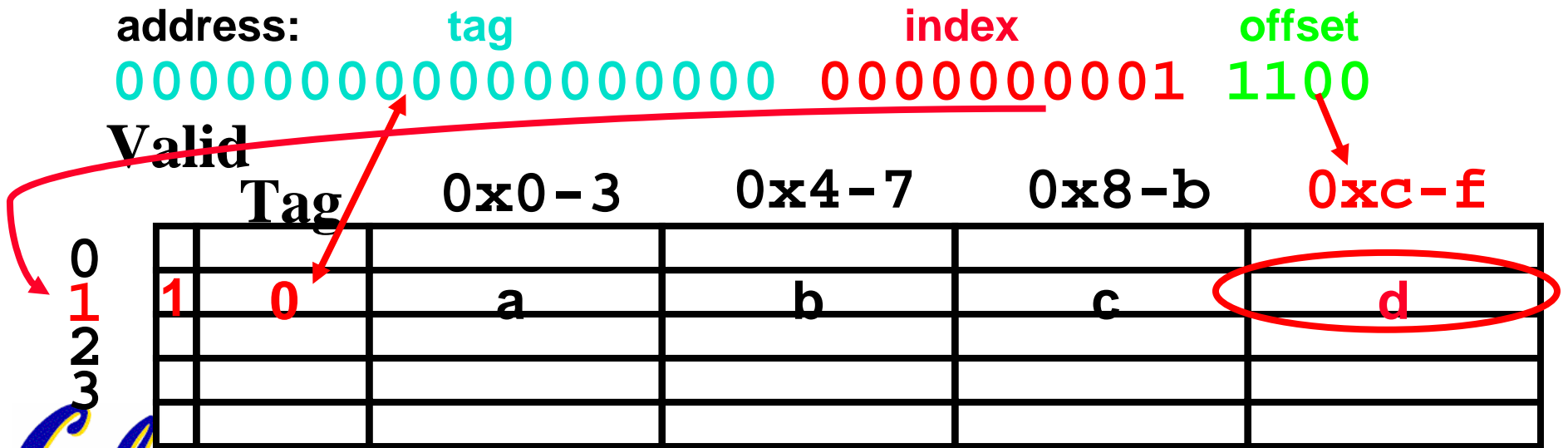


- 1989 first Intel CPU with cache on chip
- 1998 Pentium III has two levels of cache on chip



Review...

- Mechanism for transparent movement of data among levels of a storage hierarchy
 - set of address/value bindings
 - address => index to set of candidates
 - compare desired address with tag
 - service hit or miss
 - load new block and binding on miss



Block Size Tradeoff (1/3)

- **Benefits of Larger Block Size**
 - **Spatial Locality**: if we access a given word, we're likely to access other nearby words soon
 - **Very applicable with Stored-Program Concept**: if we execute a given instruction, it's likely that we'll execute the next few as well
 - **Works nicely in sequential array accesses too**



Block Size Tradeoff (2/3)

- Drawbacks of Larger Block Size
 - Larger block size means **larger miss penalty**
 - on a miss, takes longer time to load a new block from next level
 - If block size is too big relative to cache size, then there are too few blocks
 - Result: miss rate goes up
- In general, minimize **Average Memory Access Time (AMAT)**
 - = Hit Time
 - + Miss Penalty x Miss Rate

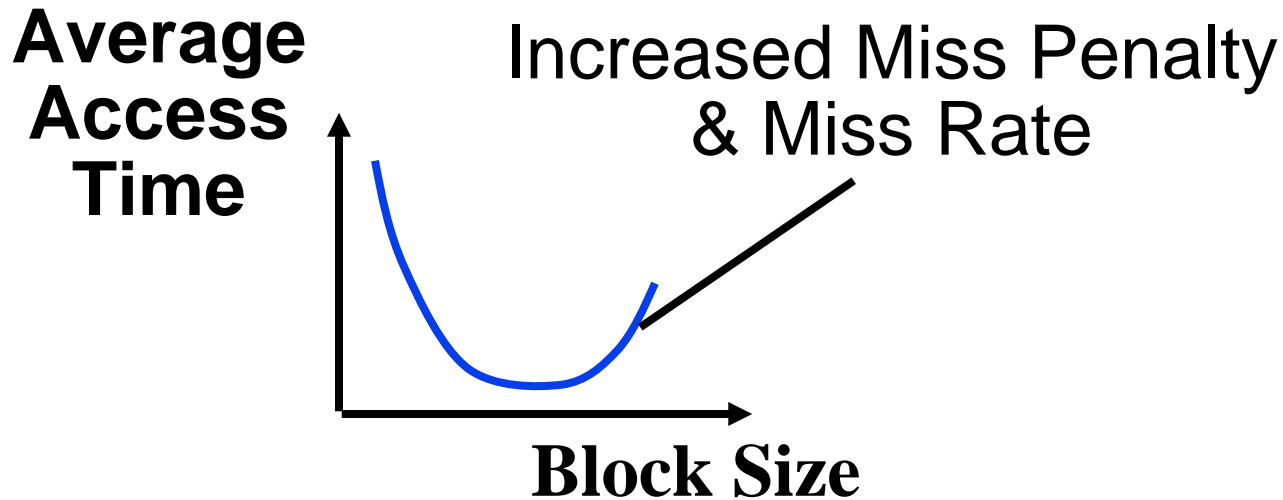
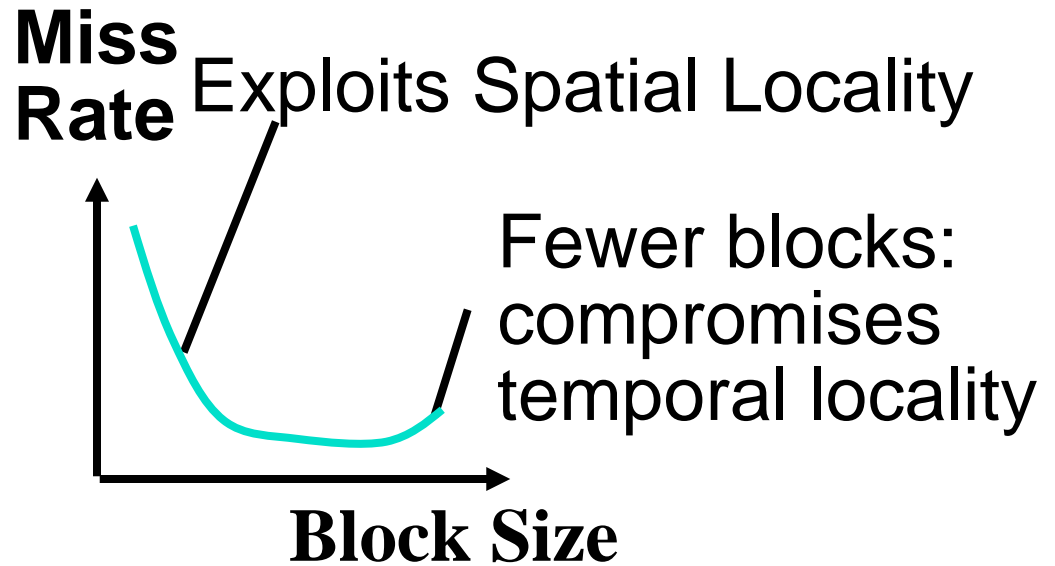
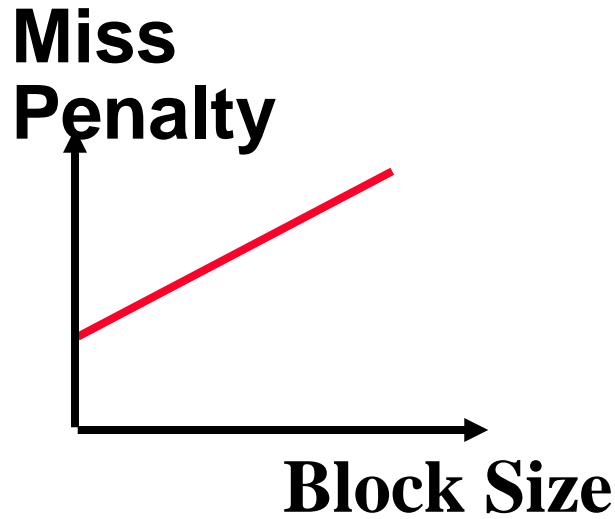


Block Size Tradeoff (3/3)

- **Hit Time** = time to find and retrieve data from current level cache
- **Miss Penalty** = average time to retrieve data on a current level miss (includes the possibility of misses on successive levels of memory hierarchy)
- **Hit Rate** = % of requests that are found in current level cache
- **Miss Rate** = $1 - \text{Hit Rate}$



Block Size Tradeoff Conclusions



Types of Cache Misses (1/2)

- “Three Cs” Model of Misses
- 1st C: Compulsory Misses
 - occur when a program is first started
 - cache does not contain any of that program’s data yet, so misses are bound to occur
 - can’t be avoided easily, so won’t focus on these in this course



Types of Cache Misses (2/2)

- **2nd C: Conflict Misses**

- miss that occurs because two distinct memory addresses map to the same cache location
- two blocks (which happen to map to the same location) can keep overwriting each other
- big problem in direct-mapped caches
- how do we lessen the effect of these?

- **Dealing with Conflict Misses**

- **Solution 1: Make the cache size bigger**
 - Fails at some point
- **Solution 2: Multiple distinct blocks can fit in the same cache Index?**



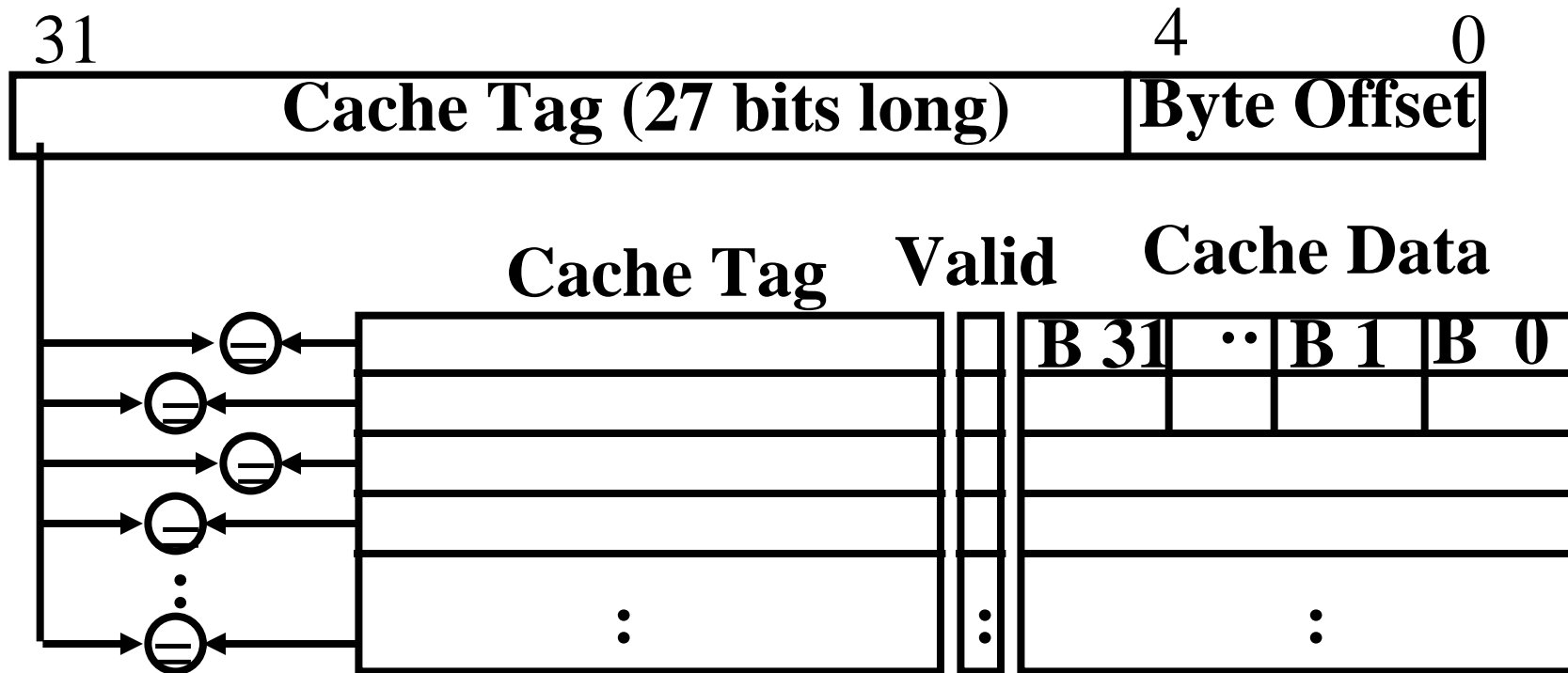
Fully Associative Cache (1/3)

- **Memory address fields:**
 - **Tag: same as before**
 - **Offset: same as before**
 - **Index: non-existent**
- **What does this mean?**
 - **no “rows”**: any block can go anywhere in the cache
 - **must compare with all tags in entire cache to see if data is there**



Fully Associative Cache (2/3)

- Fully Associative Cache (e.g., 32 B block)
 - compare tags in parallel



Fully Associative Cache (3/3)

- **Benefit of Fully Assoc Cache**
 - **No Conflict Misses (since data can go anywhere)**
- **Drawbacks of Fully Assoc Cache**
 - **Need hardware comparator for every single entry: if we have a 64KB of data in cache with 4B entries, we need 16K comparators: infeasible**



Third Type of Cache Miss

- Capacity Misses

- miss that occurs because the cache has a limited size
 - miss that would not occur if we increase the size of the cache
 - sketchy definition, so just get the general idea
- This is the primary type of miss for Fully Associative caches.



N-Way Set Associative Cache (1/4)

- **Memory address fields:**
 - **Tag: same as before**
 - **Offset: same as before**
 - **Index: points us to the correct “row” (called a set in this case)**
- **So what’s the difference?**
 - **each set contains multiple blocks**
 - **once we’ve found correct set, must compare with all tags in that set to find our data**



N-Way Set Associative Cache (2/4)

- **Summary:**
 - **cache is direct-mapped w/respect to sets**
 - **each set is fully associative**
 - **basically N direct-mapped caches working in parallel: each has its own valid bit and data**



N-Way Set Associative Cache (3/4)

- **Given memory address:**
 - **Find correct set using Index value.**
 - **Compare Tag with all Tag values in the determined set.**
 - **If a match occurs, hit!, otherwise a miss.**
 - **Finally, use the offset field as usual to find the desired data within the block.**



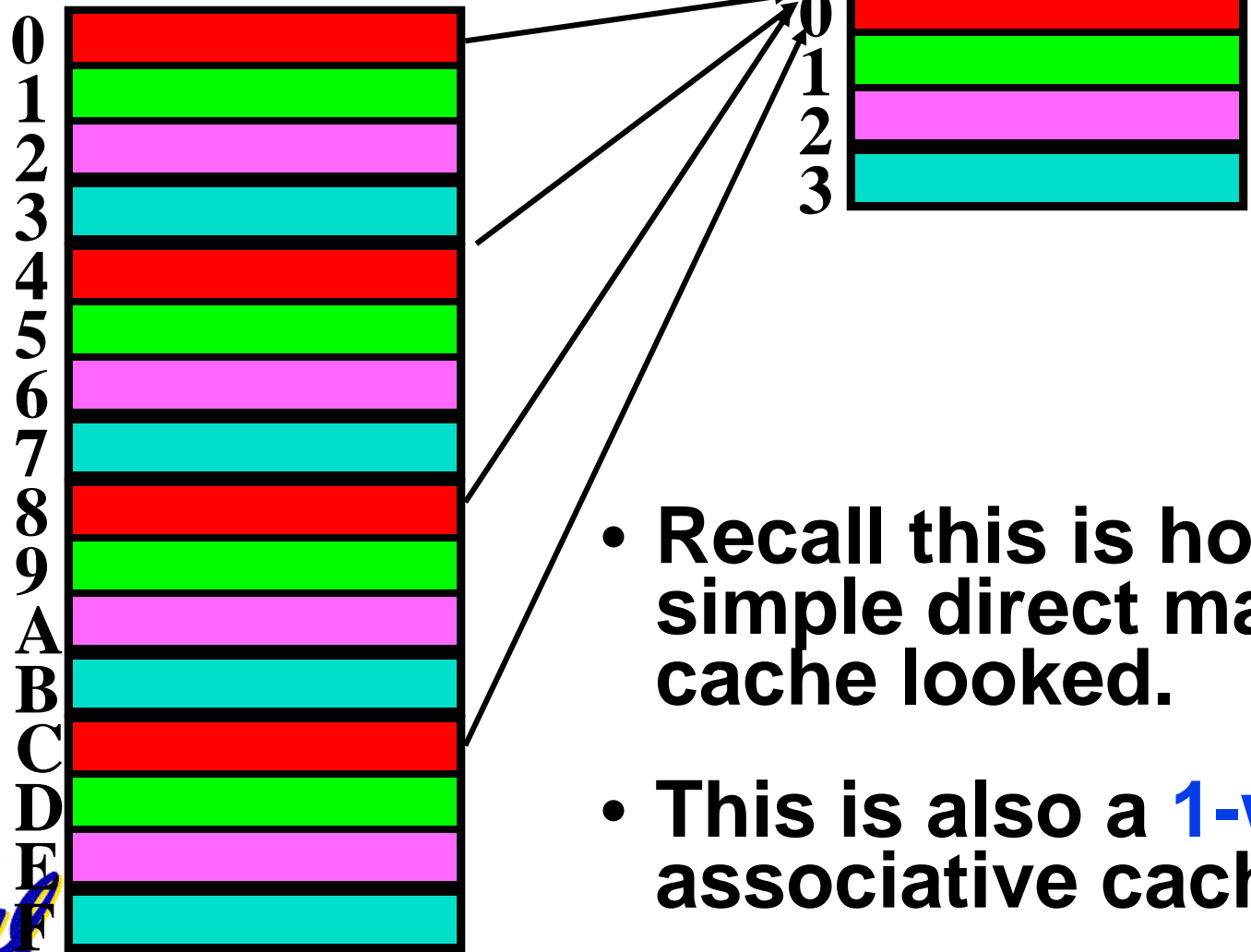
N-Way Set Associative Cache (4/4)

- **What's so great about this?**
 - **even a 2-way set assoc cache avoids a lot of conflict misses**
 - **hardware cost isn't that bad: only need N comparators**
- **In fact, for a cache with M blocks,**
 - **it's Direct-Mapped if it's 1-way set assoc**
 - **it's Fully Assoc if it's M-way set assoc**
 - **so these two are just special cases of the more general set associative design**



Associative Cache Example

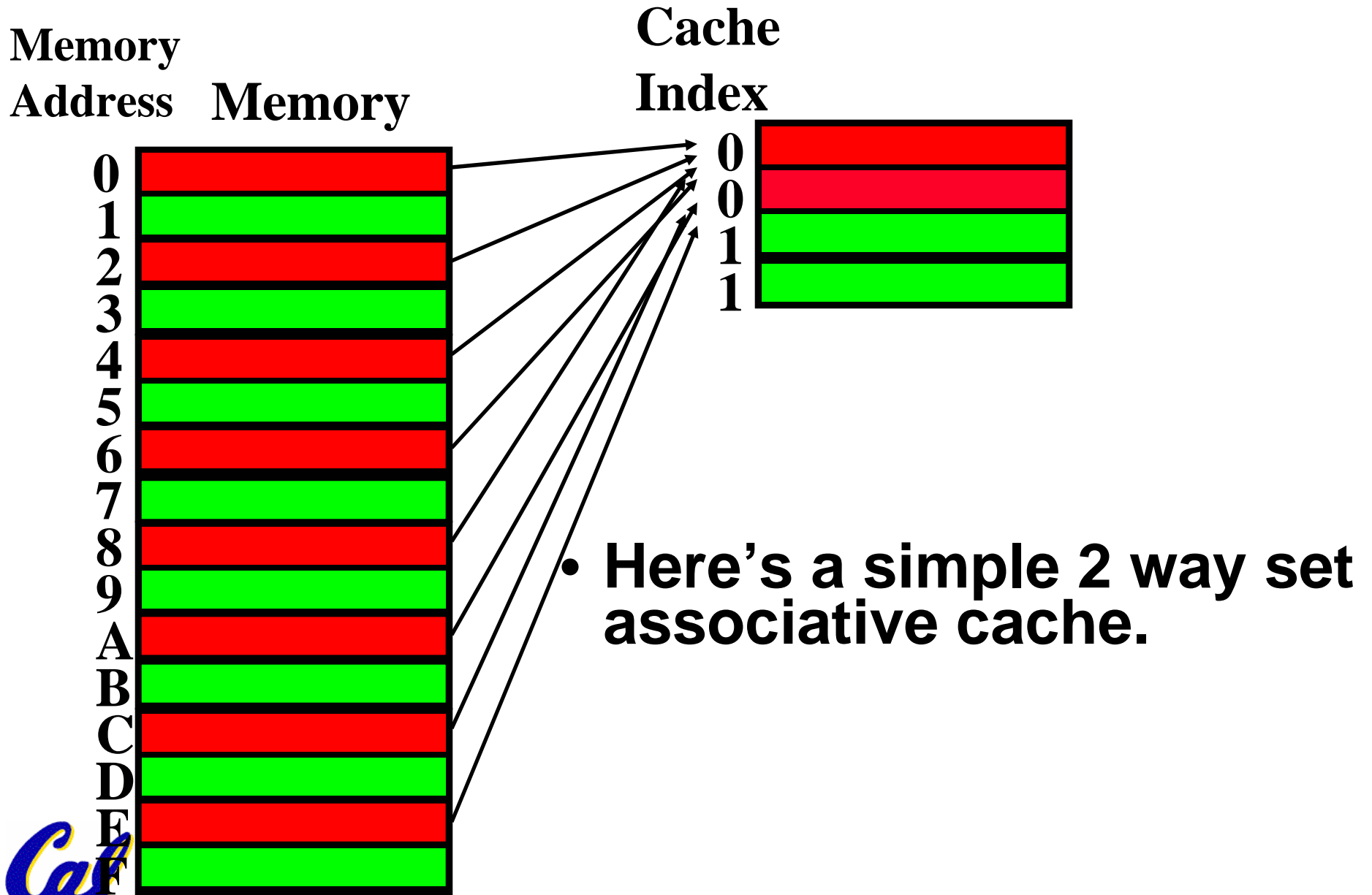
Memory Address Memory Cache Index 4 Byte Direct Mapped Cache



- Recall this is how a simple direct mapped cache looked.
- This is also a **1-way** set-associative cache!



Associative Cache Example



Pre-Exam Exercise #3

We are now going to stop for ~5 minutes. During this time, your goal is to (by yourself) come up with a potential exam exercise covering the topics of CPU Design & Pipelining. Make it as much like a real exam question as possible.

After this five minutes, you will explain your question to a small group and work through how you would go about solving it. I'll call on some random samples for the full class.



Administrivia

- **Midterm 2:**
 - **Friday, 11:00am – 2:00pm**
 - **306 Soda (HP Auditorium)**
 - **Conflicts, DSP, &&|| terrified about the drop deadline: Contact Andy ASAP**

- **HW7 Out Now, Due Sunday**
- **Project 3 Out Later This Week**



Block Replacement Policy (1/2)

- **Direct-Mapped Cache:** index completely specifies position which position a block can go in on a miss
- **N-Way Set Assoc:** index specifies a set, but block can occupy any position within the set on a miss
- **Fully Associative:** block can be written into any position
- **Question:** if we have the choice, where should we write an incoming block?



Block Replacement Policy (2/2)

- If there are any locations with valid bit off (empty), then usually write the new block into the first one.
- If all possible locations already have a valid block, we must pick a **replacement policy**: rule by which we determine which block gets “cached out” on a miss.



Block Replacement Policy: LRU

- **LRU (Least Recently Used)**

- **Idea: cache out block which has been accessed (read or write) least recently**
- **Pro: temporal locality \Rightarrow recent past use implies likely future use: in fact, this is a very effective policy**
- **Con: with 2-way set assoc, easy to keep track (one LRU bit); with 4-way or greater, requires complicated hardware and more time to keep track of this**



Block Replacement Example

- We have a 2-way set associative cache with a four word *total* capacity and one word blocks. We perform the following word accesses (ignore bytes for this problem):

0, 2, 0, 1, 4, 0, 2, 3, 5, 4

How many hits and how many misses will there be for the LRU block replacement policy?



Block Replacement Example: LRU

• Addresses 0, 2, 0, 1, 4, 0, ...
 0: miss, bring into set 0 (loc 0)

2: miss, bring into set 0 (loc 1)

0: hit

1: miss, bring into set 1 (loc 0)

4: miss, bring into set 0 (loc 1, replace 2)

0: hit

	loc 0	loc 1
set 0	0	lru
set 1		
set 0	0	2
set 1		
set 0	0	2
set 1		
set 0	0	2
set 1	1	lru
set 0	0	4
set 1	1	lru
set 0	0	4
set 1	1	lru



Big Idea

- How to choose between associativity, block size, replacement policy?
- Design against a performance model
 - Minimize: *Average Memory Access Time*
= Hit Time
+ Miss Penalty x Miss Rate
 - influenced by technology & program behavior
 - Note: Hit Time encompasses Hit Rate!!!
- Create the illusion of a memory that is large, cheap, and fast - on average



Example

- **Assume**
 - **Hit Time = 1 cycle**
 - **Miss rate = 5%**
 - **Miss penalty = 20 cycles**
 - **Calculate AMAT...**
- **Avg mem access time**
 - = 1 + 0.05 x 20**
 - = 1 + 1 cycles**
 - = 2 cycles**



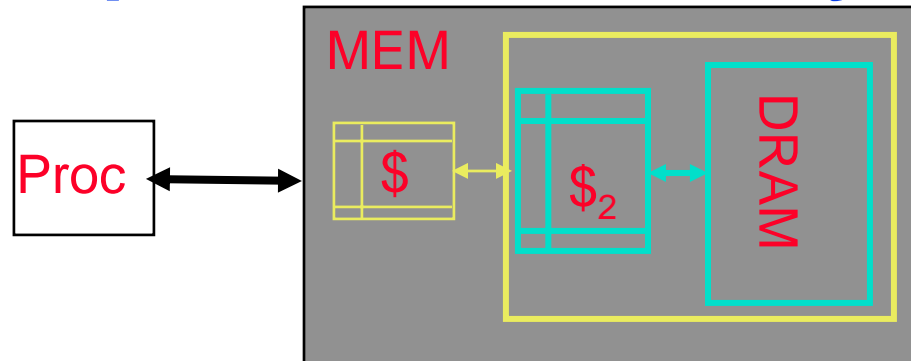
Ways to reduce miss rate

- **Larger cache**
 - limited by cost and technology
 - hit time of first level cache $<$ cycle time
- **More places in the cache to put each block of memory – associativity**
 - **fully-associative**
 - any block any line
 - **N-way set associated**
 - N places for each block
 - direct map: $N=1$



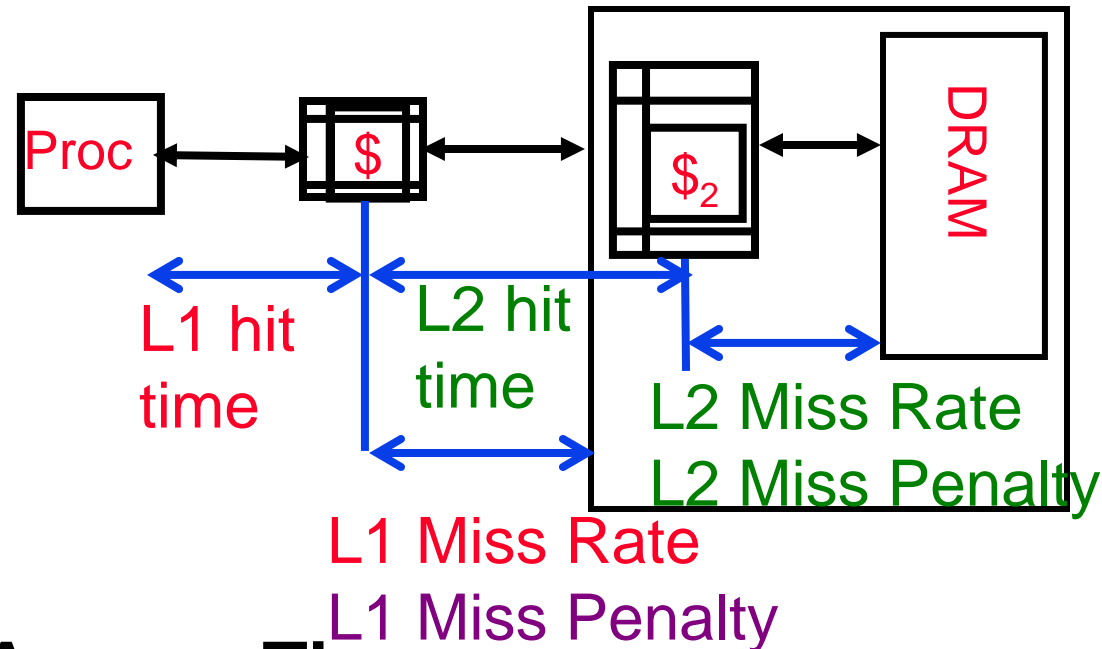
Improving Miss Penalty

- When caches first became popular, Miss Penalty ~ 10 processor clock cycles
- Slightly more modern:
2400 MHz Processor (0.4 ns per clock cycle) and 80 ns to go to DRAM
⇒ **200 processor clock cycles!**



Solution: another cache between memory and the processor cache: Second Level (L2) Cache

Analyzing Multi-level cache hierarchy



Avg Mem Access Time =

$$\frac{\text{L1 Hit Time} + \text{L1 Miss Rate} * \text{L1 Miss Penalty}}{\text{L1 Miss Penalty} =}$$

L1 Miss Penalty =

$$\frac{\text{L2 Hit Time} + \text{L2 Miss Rate} * \text{L2 Miss Penalty}}{\text{L1 Miss Penalty} =}$$

Avg Mem Access Time =

$$\text{L1 Hit Time} + \text{L1 Miss Rate} *$$

$$(\text{L2 Hit Time} + \text{L2 Miss Rate} * \text{L2 Miss Penalty})$$



Typical Scale

- **L1**
 - **size: tens of KB**
 - **hit time: complete in one clock cycle**
 - **miss rates: 1-5%**
- **L2:**
 - **size: hundreds of KB**
 - **hit time: few clock cycles**
 - **miss rates: 10-20%**
- **L2 miss rate is fraction of L1 misses that also miss in L2**
 - **why so high?**



Example: with L2 cache

- **Assume**
 - L1 Hit Time = 1 cycle
 - L1 Miss rate = 5%
 - L2 Hit Time = 5 cycles
 - L2 Miss rate = 15% (% L1 misses that miss)
 - L2 Miss Penalty = **200 cycles**
- L1 miss penalty = $5 + 0.15 * 200 = 35$
- Avg mem access time = $1 + 0.05 * 35$
= **2.75 cycles**



Example: without L2 cache

- Assume
 - L1 Hit Time = 1 cycle
 - L1 Miss rate = 5%
 - L1 Miss Penalty = 200 cycles
- Avg mem access time = $1 + 0.05 \times 200$
= 11 cycles
- 4x faster with L2 cache! (2.75 vs. 11)



What to do on a write hit?

- **Write-through**

- update the word in cache block and corresponding word in memory

- **Write-back**

- update word in cache block
- allow memory word to be “stale”

⇒ add ‘dirty’ bit to each block indicating that memory needs to be updated when block is replaced

⇒ OS flushes cache before I/O...

- **Performance trade-offs?**



An Actual CPU – Pentium M

Intel® Pentium®
M Processor



New Micro Architecture

77 Million Transistors



Micro-Ops Fusion –
fuses operations
together to enable
faster execution of
instructions at lower
power

Advanced Branch
Prediction – fewer re-dos
for increased performance

1MB Power
Optimized L2 Cache
– enables higher CPU
performance

Streaming SIMD
Extensions II
compatible with
Pentium® 4
Processor
optimized software

Dedicated Stack
Management –
faster instruction
at lower power
levels

Enhanced Intel®
SpeedStep®
Technology - Multiple
voltages & frequency
operating points

400 MHz Power
Optimized System Bus
- faster system bus to
enhance performance at
lower power levels



intel.

Peer Instructions

1. In the last 10 years, the gap between the access time of DRAMs & the cycle time of processors has decreased. (I.e., is closing)
2. A 2-way set-associative cache can be outperformed by a direct-mapped cache.
3. Larger block size \Rightarrow lower miss rate



Peer Instructions Answer

1. That was one of the motivation for caches in the first place -- that the memory gap is big and widening.
2. Sure, consider the caches from the previous slides with the following workload: 0, 2, 0, 4, 2
2-way: 0m, 2m, 0h, 4m, 2m; DM: 0m, 2m, 0h, 4m, 2h
3. Larger block size \Rightarrow lower miss rate, true until a certain point, and then the ping-pong effect takes over
 1. In the last 10 years, the gap between the access time of DRAMs & the cycle time of processors has decreased. (I.e., is closing)
 2. A 2-way set-associative cache can be outperformed by a direct-mapped cache.
 3. Larger block size \Rightarrow lower miss rate



And in Conclusion...

- **Cache design choices:**
 - size of cache: speed v. capacity
 - direct-mapped v. associative
 - for N-way set assoc: choice of N
 - block replacement policy
 - 2nd level cache?
 - 3rd level cache?
 - Write through v. write back?
- **Use performance model to pick between choices, depending on programs, technology, budget, ...**

