COMP303 Computer Architecture Lecture 15

Calculating and Improving Cache Performance

Cache Performance Measures

- *Hit rate* : fraction found in the cache
  - So high that we usually talk about *Miss rate = 1 - Hit Rate*
- *Hit time* : time to access the cache
- *Miss penalty* : time to replace a block from lower level, including time to replace in CPU
  - *access time* : time to access lower level
  - *transfer time* : time to transfer block
- Average memory-access time (AMAT)

  = Hit time + Miss rate x Miss penalty (ns or clocks)

Measuring and Analyzing Cache Performance

- CPU time can be divided into two parts:

CPU time = (CPU execution clock cycles + Memory-stall clock cycles) x Clock cycle time

Memory-stall clock cycles = Read-stall cycles + Write-stall cycles

$$\text{Read-stall cycles} = \frac{\text{Reads}}{\text{Program}} \text{ X Read miss rate x Read miss penalty}$$

$$\text{Write-stall cycles} = \left(\frac{\text{Writes}}{\text{Program}} \text{ X Write miss rate x Write miss penalty} \right)$$

+ Write buffer stall → Can be ignored using reasonable write buffer

Measuring and Analyzing Cache Performance

- Read and Write stall cycles can be combined by using single miss rate and miss penalty (the write and read miss penalties are the same, i.e. time to fetch a block from MM)

$$\text{Memory-stall clock cycles} = \frac{\text{Memory accesses}}{\text{Program}} \times \text{Miss rate} \times \text{Miss penalty}$$

- It can also be written as :

$$\text{Memory-stall clock cycles} = \frac{\text{Instructions}}{\text{Program}} \times \frac{\text{Miss}}{\text{Instruction}} \times \text{Miss penalty}$$

Example: Cache Performance (page 565)

- Assume that:
  - Instruction miss rate %2
  - Data miss rate %4
  - CPI is 2 (without any memory stalls)
  - Miss penalty 40 cycles
  - %36 of instructions are load/store
- Determine how much faster a machine would run with a perfect cache that never missed.

Instruction miss cycles = I x 0.02 x 40 = 0.80 I (**I** is # of instructions)

Data miss cycles = I x 0.36 x 0.04 x 40 = 0.58 I

Total memory stall cycles = 0.80 I + 0.58 I = 1.38 I

CPI_{stall} = 2 + 1.38 = 3.38

$$\frac{\text{CPU time with stalls}}{\text{CPU time with perfect cache}} = \frac{I \times CPI_{stall} \times \text{Clock cycle}}{I \times CPI_{perfect} \times \text{Clock cycle}} = \frac{3.38}{2} = 1.69$$

Cache Performance with Increased Clock Rate

- Suppose that clock rate of the machine used in the previous example is doubled but the memory speed, cache misses, and miss rate are same. How much faster the machine be with the faster clock?

Since the clock rate is doubled, new miss penalty will be 2x40=80 clock cycles.

Total memory stall cycles = (0.02 x 80) + 0.36 x (0.04 x 80) = 2.75

$$CPI_{\text{fast clock}} = 2 + 2.75 = 4.75$$

$$\frac{\text{CPU time with slow clock}}{\text{CPU time with fast clock}} = \frac{I \times CPI_{\text{slow clock}} \times \text{Clock cycle}}{I \times CPI_{\text{fast clock}} \times \frac{\text{Clock cycle}}{2}}$$

$$= \frac{3.38 \times 2}{4.75} = 1.41$$

Calculating AMAT

- If a direct mapped cache has a hit rate of 95%, a hit time of 4 ns, and a miss penalty of 100 ns, what is the AMAT?

  AMAT = Hit time + Miss rate x Miss penalty = 4 + 0.05 x 100 = 9 ns

- If replacing the cache with a 2-way set associative increases the hit rate to 97%, but increases the hit time to 5 ns, what is the new AMAT?

  AMAT = Hit time + Miss rate x Miss penalty = 5 + 0.03 x 100 = 8 ns

Split vs. Unified Cache

- **Unified cache** (mixed cache): Data and instructions are stored together (von Neuman architecture)
- **Split cache**: Data and instructions are stored separately (Harvard architecture)
- Why do instructions caches have a lower miss ratio?

Size	Instruction Cache	Data Cache	Unified Cache
1 KB	3.06%	24.61%	13.34%
2 KB	2.26%	20.57%	9.78%
4 KB	1.78%	15.94%	7.24%
8 KB	1.10%	10.19%	4.57%
16 KB	0.64%	6.47%	2.87%
32 KB	0.39%	4.82%	1.99%
64 KB	0.15%	3.77%	1.35%
128 KB	0.02%	2.88%	0.95%

Example: Split vs. Unified Cache

- Which has the lower average memory access time?
  - Split cache : 16 KB instructions + 16 KB data
  - Unified cache: 32 KB (instructions + data)
- Assumptions
  - Use miss rates from previous chart
  - Miss penalty is 50 cycles
  - Hit time is 1 cycle
  - 75% of the total memory accesses for instructions and 25% of the total memory accesses for data
  - On the unified cache, a load or store hit takes an extra cycle, since there is only one port for instructions and data

Example: Split vs. Unified Cache

Average memory-access time = Hit time + Miss rate x Miss penalty

AMAT = %instr x (instr hit time + instr miss rate x instr miss penalty) +
%data x (data hit time + data miss rate x data miss penalty)

For the split cache:

AMAT = 75% x (1 + 0.64% x 50) + 25% (1 + 6.47% x 50) = 2.05

For the unified cache

AMAT = 75% x (1 + 1.99% x 50) + 25% x (**2** + 1.99% x 50) = 2.24

The unified cache has a longer AMAT, even though its miss rate is lower, due to conflicts for instruction and data hazards.

Improving Cache Performance

- Average memory-access time

  = Hit time + Miss rate x Miss penalty

- Improve performance by:

  1. Reduce the miss rate,
  2. Reduce the miss penalty, or
  3. Reduce the time to hit in the cache.

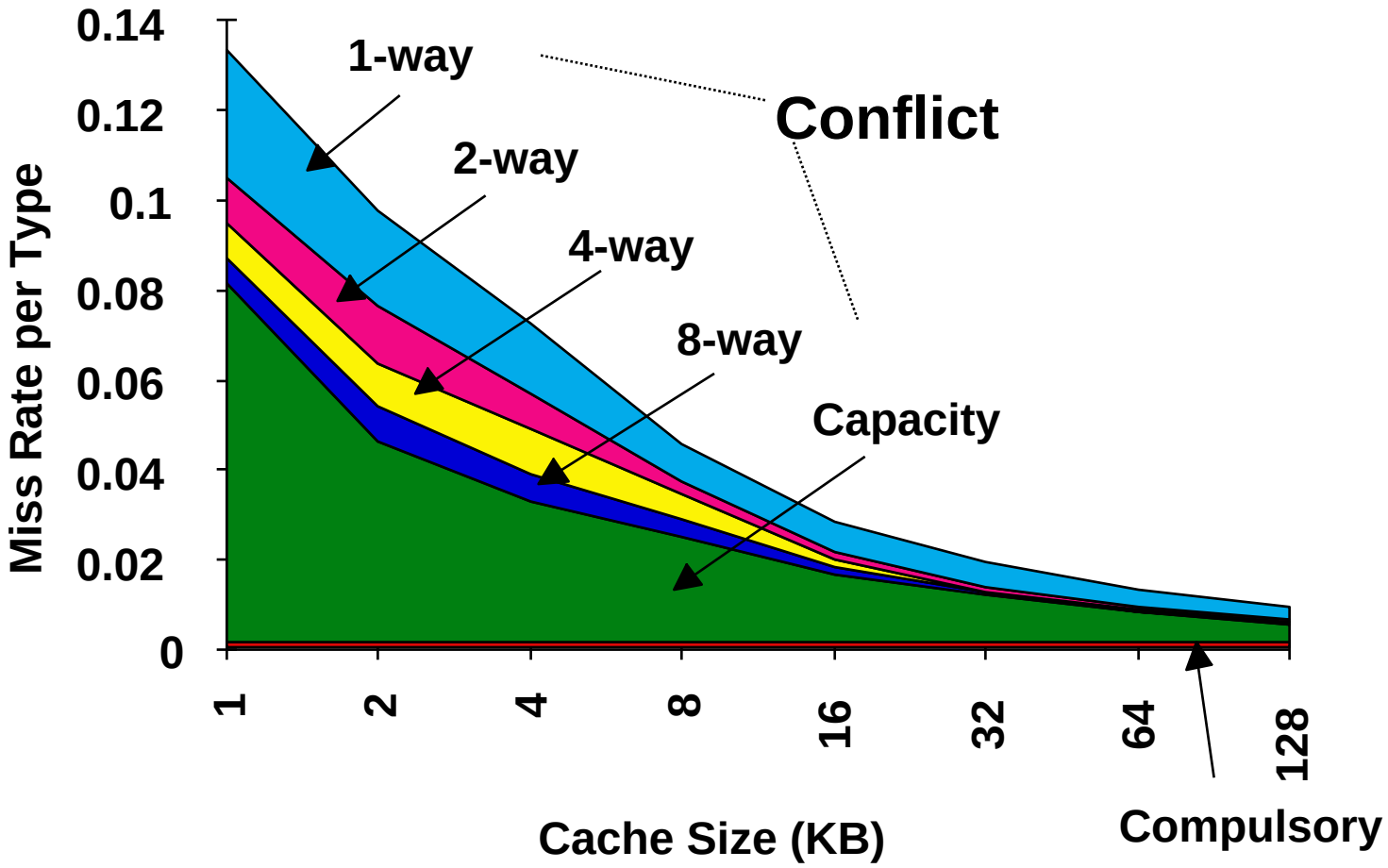
Reducing Misses

- Classifying Misses: 3 Cs
  - *Compulsory*—The first access to a block is not in the cache, so the block must be brought into the cache. These are also called *cold start misses* or *first reference misses*.
    (Misses in infinite cache)
  - *Capacity*—If the cache cannot contain all the blocks needed during execution of a program, capacity misses will occur due to blocks being discarded and later retrieved.
    (Misses due to size of cache)
  - *Conflict*—If the block-placement strategy is set associative or direct mapped, conflict misses (in addition to compulsory and capacity misses) will occur because a block can be discarded and later retrieved if too many blocks map to its set. These are also called *collision misses* or *interference misses*.
    (Misses due to associative and size of cache)

Increasing Cache Size

- One way to decrease misses is to increase the cache size
  - Reduces capacity and conflict misses
  - No effect on compulsory misses
- However a larger cache may increase the hit time
  - larger cache => larger access time
  - If cache is too large, can't fit it on the same chip as processor.

3Cs Absolute Miss Rate

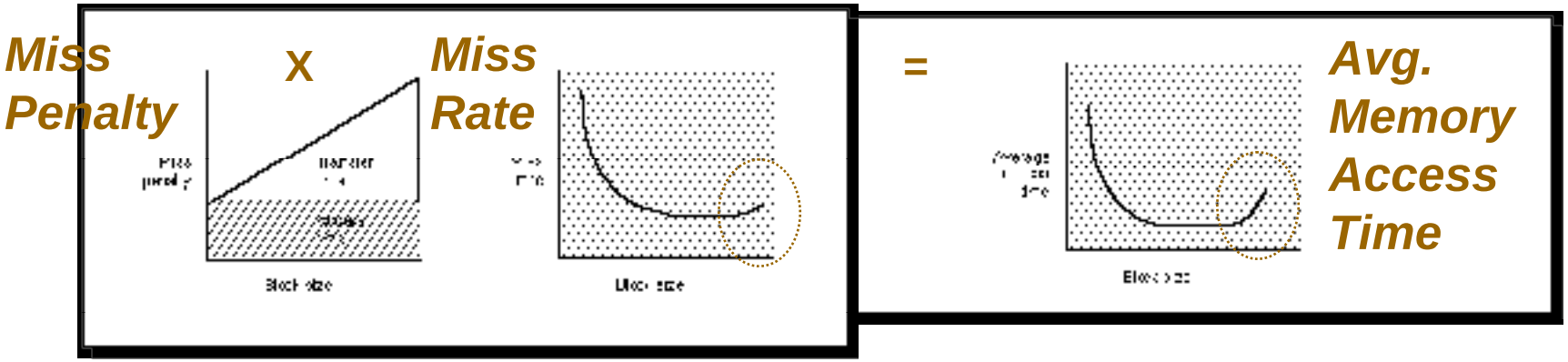


Increasing Block Size

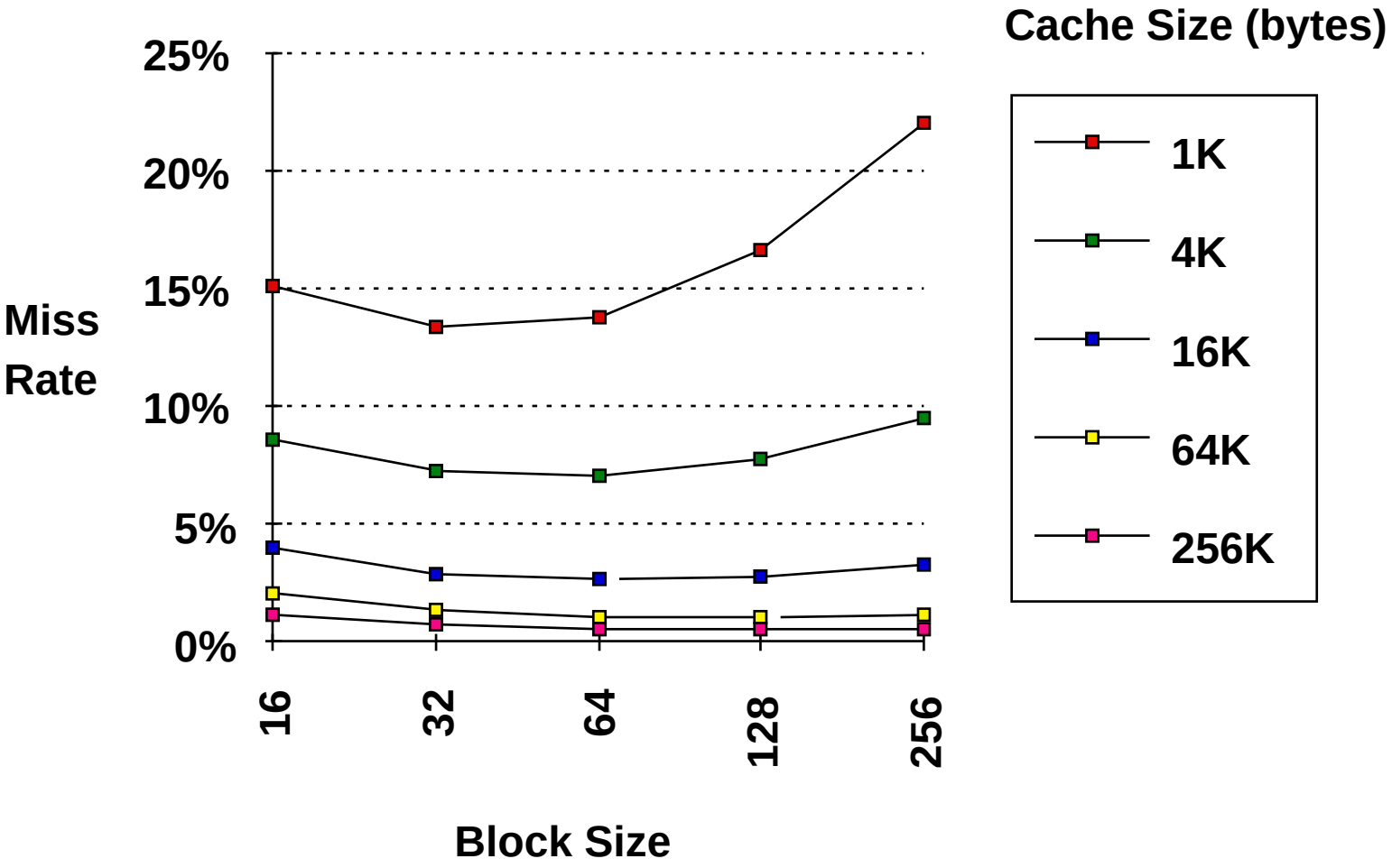
- Another way to reduce the miss rate is to increase the block size
  - Take advantage of spatial locality
  - Decreases compulsory misses
- However, larger blocks have disadvantages
  - May increase the miss penalty (need to get more data)
  - May increase hit time (need to read more data from cache and larger mux)
  - May increase miss rate, since conflict misses
- Increasing the block size can help, but don’t overdo it.

Block Size vs. Cache Measures

- Increasing Block Size generally increases Miss Penalty and decreases Miss Rate
- As the block size increases the AMAT starts to decrease, but eventually increases



Increasing Block Size



Increasing Associativity

- Increasing associativity helps reduce conflict misses
- 2:1 Cache Rule:
  - The miss rate of a direct mapped cache of size N is about equal to the miss rate of a 2-way set associative cache of size N/2
  - For example, the miss rate of a 32 Kbyte direct mapped cache is about equal to the miss rate of a 16 Kbyte 2-way set associative cache
- Disadvantages of higher associativity
  - Need to do large number of comparisons
  - Need n-to-1 multiplexor for n-way set associative
  - Could increase hit time

AMAT vs. Associativity

Cache Size	Associativity			
(KB)	1-way	2-way	4-way	8-way
1	7.65	6.60	6.22	5.44
2	5.90	4.90	4.62	4.09
4	4.60	3.95	3.57	3.19
8	3.30	3.00	2.87	2.59
16	2.45	2.20	2.12	2.04
32	2.00	1.80	1.77	1.79
64	1.70	1.60	1.57	1.59
128	1.50	1.45	1.42	1.44

Red means A.M.A.T. not improved by more associativity

Using a 2nd Level Cache

- A second level (L2) cache reduces the miss penalty by providing a large cache between the first level (L1) cache and main memory
- L2 Equations

$$\text{AMAT} = \text{Hit Time}_{L1} + \text{Miss Rate}_{L1} \times \text{Miss Penalty}_{L1}$$

$$\text{Miss Penalty}_{L1} = \text{Hit Time}_{L2} + \text{Miss Rate}_{L2} \times \text{Miss Penalty}_{L2}$$

$$\text{AMAT} = \text{Hit Time}_{L1} + \text{Miss Rate}_{L1} \times (\text{Hit Time}_{L2} + \text{Miss Rate}_{L2} \times \text{Miss Penalty}_{L2})$$

Adding an L2 Cache

- If a direct mapped cache has a hit rate of 95%, a hit time of 4 ns, and a miss penalty of 100 ns, what is the AMAT?

  AMAT = Hit time + Miss rate x Miss penalty = 4 + 0.05 x 100 = 9 ns

- If an L2 cache is added with a hit time of 20 ns and a hit rate of 50%, what is the new AMAT?

  AMAT = Hit Time_{L1} + Miss Rate_{L1} x (Hit Time_{L2} + Miss Rate_{L2} x Miss Penalty_{L2})

  = 4 + 0.05 x (20 + 0.5x100) = 7.5 ns

Cache Performance Summary

- AMAT = Hit time + Miss rate x Miss penalty
- Split vs. Unified Cache
- 3 C's of misses
  - compulsory
  - capacity
  - conflict
- Methods for improving performance
  - increase (change) cache size
  - increase (change) block size
  - increase (change) associativity
  - add a 2nd level cache