Improving Cache Performance

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

Thanks to UC Berkeley CS 252 website for many of these slides.

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. Also called cold start misses or first reference misses. (Misses in even an 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 in Fully Associative Size X Cache)
  - **Conflict**—If block-placement strategy is set associative or direct mapped, conflict misses (in addition to compulsory & capacity misses) will occur because a block can be discarded and later retrieved if too many blocks map to its set. Also called collision misses or interference misses. (Misses in N-way Associative, Size X Cache)

- **More recent, 4th “C”: Coherence - Misses**
3Cs Absolute Miss Rate (SPEC92)

2:1 Cache Rule

miss rate 1-way associative cache size $X$
= miss rate 2-way associative cache size $X/2$
How Can Reduce Misses?

- 3 Cs: Compulsory, Capacity, Conflict
- In all cases, assume total cache size not changed:
  - What happens if:
    1) Change Block Size:
       Which of 3Cs is obviously affected?
    2) Change Associativity:
       Which of 3Cs is obviously affected?
    3) Change Compiler:
       Which of 3Cs is obviously affected?
1. Reduce Misses via Larger Block Size

![Graph showing the relationship between block size and miss rate for different cache sizes.

2. Reduce Misses via Higher Associativity

- **2:1 Cache Rule:**
  - Miss Rate DM cache size $N$ \_ Miss Rate 2-way cache size $N/2$

- **Beware:** Execution time is only final measure!
  - Will Clock Cycle time increase?
  - Hill [1988] suggested hit time for 2-way vs. 1-way external cache +10%, internal + 2%
Example: Avg. Memory Access Time vs. Miss Rate

- Example: assume CCT = 1.10 for 2-way, 1.12 for 4-way, 1.14 for 8-way vs. CCT direct mapped

<table>
<thead>
<tr>
<th>Cache Size (KB)</th>
<th>1-way</th>
<th>2-way</th>
<th>4-way</th>
<th>8-way</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2.33</td>
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</tr>
<tr>
<td>128</td>
<td>1.10</td>
<td>1.17</td>
<td>1.18</td>
<td>1.20</td>
</tr>
</tbody>
</table>

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

3. Reducing Misses via a “Victim Cache”

- How to combine fast hit time of direct mapped yet still avoid conflict misses?
- Add buffer to place data discarded from cache
- Jouppi [1990]: 4-entry victim cache removed 20% to 95% of conflicts for a 4 KB direct mapped data cache
- Used in Alpha, HP machines
4. Reducing Misses via “Pseudo-Associativity”

- How to combine fast hit time of Direct Mapped and have the lower conflict misses of 2-way SA cache?
- Divide cache: on a miss, check other half of cache to see if there, if so have a pseudo-hit (slow hit)

<table>
<thead>
<tr>
<th>Hit Time</th>
<th>Miss Penalty</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pseudo Hit Time</td>
<td></td>
</tr>
</tbody>
</table>

- Drawback: CPU pipeline is hard if hit takes 1 or 2 cycles
  - Better for caches not tied directly to processor (L2)
  - Used in MIPS R1000 L2 cache, similar in UltraSPARC

5. Reducing Misses by Hardware Prefetching of Instructions & Datals

- E.g., Instruction Prefetching
  - Alpha 21064 fetches 2 blocks on a miss
  - Extra block placed in “stream buffer”
  - On miss check stream buffer
- Works with data blocks too:
  - Jouppi [1990] 1 data stream buffer got 25% misses from 4KB cache; 4 streams got 43%
  - Palacharla & Kessler [1994] for scientific programs for 8 streams got 50% to 70% of misses from 2 64KB, 4-way set associative caches
- Prefetching relies on having extra memory bandwidth that can be used without penalty
6. Reducing Misses by Software Prefetching Data

- Data Prefetch
  - Load data into register (HP PA-RISC loads)
  - Cache Prefetch: load into cache (MIPS IV, PowerPC, SPARC v. 9)
  - Special prefetching instructions cannot cause faults; a form of speculative execution

- Prefetching comes in two flavors:
  - Binding prefetch: Requests load directly into register.
    - Must be correct address and register!
  - Non-Binding prefetch: Load into cache.
    - Can be incorrect. Frees HW/SW to guess!

- Issuing Prefetch Instructions takes time
  - Is cost of prefetch issues < savings in reduced misses?
  - Higher superscalar reduces difficulty of issue bandwidth

7. Reducing Misses by Compiler Optimizations

- McFarling [1989] reduced caches misses by 75% on 8KB direct mapped cache, 4 byte blocks in software

  - Instructions
    - Reorder procedures in memory so as to reduce conflict misses
    - Profiling to look at conflicts (using tools they developed)

  - Data
    - Merging Arrays: improve spatial locality by single array of compound elements vs. 2 arrays
    - Loop Interchange: change nesting of loops to access data in order stored in memory
    - Loop Fusion: Combine 2 independent loops that have same looping and some variables overlap
    - Blocking: Improve temporal locality by accessing "blocks" of data repeatedly vs. going down whole columns or rows
Merging Arrays Example

/* Before: 2 sequential arrays */
int val[SIZE];
int key[SIZE];

/* After: 1 array of structures */
struct merge {
    int val;
    int key;
};
struct merge merged_array[SIZE];

Reducing conflicts between val & key;
improve spatial locality

Loop Interchange Example

/* Before */
for (k = 0; k < 100; k = k+1)
    for (j = 0; j < 100; j = j+1)
        for (i = 0; i < 5000; i = i+1)
            x[i][j] = 2 * x[i][j];

/* After */
for (k = 0; k < 100; k = k+1)
    for (i = 0; i < 5000; i = i+1)
        for (j = 0; j < 100; j = j+1)
            x[i][j] = 2 * x[i][j];

Sequential accesses instead of striding
through memory every 100 words; improved
spatial locality
Loop Fusion Example

/* Before */
for (i = 0; i < N; i = i+1)
  for (j = 0; j < N; j = j+1)
    a[i][j] = 1/b[i][j] * c[i][j];
for (i = 0; i < N; i = i+1)
  for (j = 0; j < N; j = j+1)
    d[i][j] = a[i][j] + c[i][j];
/* After */
for (i = 0; i < N; i = i+1)
  for (j = 0; j < N; j = j+1)
    {a[i][j] = 1/b[i][j] * c[i][j];
     d[i][j] = a[i][j] + c[i][j];}

2 misses per access to a & c vs. one miss per access; improve spatial locality

Blocking Example

/* Before */
for (i = 0; i < N; i = i+1)
  for (j = 0; j < N; j = j+1)
    {r = 0;
     for (k = 0; k < N; k = k+1)
       r = r + y[i][k]*z[k][j];
     x[i][j] = r;
    }

• Two Inner Loops:
  - Read all NxN elements of z[]
  - Read N elements of 1 row of y[] repeatedly
  - Write N elements of 1 row of x[]

• Capacity Misses a function of N & Cache Size:
  - 2N³ + N² => (assuming no conflict; otherwise …)

• Idea: compute on BxB submatrix that fits
**Blocking Example**

/* After */
for (jj = 0; jj < N; jj = jj+B)
for (kk = 0; kk < N; kk = kk+B)
for (i = 0; i < N; i = i+1)
  for (j = jj; j < min(jj+B-1,N); j = j+1)
    {r = 0;
     for (k = kk; k < min(kk+B-1,N); k = k+1) {
       r = r + y[i][k]*z[k][j];
     }
    }
    x[i][j] = x[i][j] + r;

• B called **Blocking Factor**
• Capacity Misses from $2N^3 + N^2$ to $N^3/B + 2N^2$
• Conflict Misses Too?

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**Reducing Conflict Misses by Blocking**

- Conflict misses in caches not FA vs. Blocking size
- Lam et al [1991] a blocking factor of 24 had a fifth the misses vs. 48 despite both fit in cache
Summary of Compiler Optimizations to Reduce Cache Misses (by hand)

- vpenta (nasa7)
- gmy (nasa7)
- tomcatv
- btrix (nasa7)
- mxm (nasa7)
- spice
- cholesky
- (nasa7)
- compress

Performance Improvement

Summary: Miss Rate Reduction

\[ CPUtime = IC \times CPI_{\text{exec}} \times \left( \frac{\text{Memory accesses}}{\text{Instruction}} \times \text{Miss rate} \times \text{Miss penalty} \right) \times \text{Clock cycle time} \]

- 3 Cs: Compulsory, Capacity, Conflict
  1. Reduce Misses via Larger Block Size
  2. Reduce Misses via Higher Associativity
  3. Reducing Misses via Victim Cache
  4. Reducing Misses via Pseudo-Associativity
  5. Reducing Misses by HW Prefetching Instr, Data
  6. Reducing Misses by SW Prefetching Data
  7. Reducing Misses by Compiler Optimizations

- Prefetching comes in two flavors:
  - Binding prefetch: Requests load directly into register.
    » Must be correct address and register!
  - Non-Binding prefetch: Load into cache.
    » Can be incorrect. Frees HW/SW to guess!
Review: Improving Cache Performance

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

Write Policy:
Write-Through vs Write-Back

- Write-through: all writes update cache and underlying memory/cache
  - Can always discard cached data - most up-to-date data is in memory
  - Cache control bit: only a valid bit
- Write-back: all writes simply update cache
  - Can’t just discard cached data - may have to write it back to memory
  - Cache control bits: both valid and dirty bits

- Other Advantages:
  - Write-through:
    » memory (or other processors) always have latest data
    » Simpler management of cache
  - Write-back:
    » much lower bandwidth, since data often overwritten multiple times
    » Better tolerance to long-latency memory?
Write Policy 2:
Write Allocate vs Non-Allocate
(What happens on write-miss)

- Write allocate: allocate new cache line in cache
  - Usually means that you have to do a “read miss” to fill in rest of the cache-line!
  - Alternative: per/word valid bits
- Write non-allocate (or “write-around”):
  - Simply send write data through to underlying memory/cache - don’t allocate new cache line!

1. Reducing Miss Penalty:
Read Priority over Write on Miss
1. Reducing Miss Penalty:
Read Priority over Write on Miss

- Write-through with write buffers offer RAW conflicts with main memory reads on cache misses
  - If simply wait for write buffer to empty, might increase read miss penalty (old MIPS 1000 by 50%)
  - Check write buffer contents before read; if no conflicts, let the memory access continue
- Write-back also want buffer to hold misplaced blocks
  - Read miss replacing dirty block
  - Normal: Write dirty block to memory, and then do the read
  - Instead copy the dirty block to a write buffer, then do the read, and then do the write
  - CPU stall less since restarts as soon as do read

2. Reduce Miss Penalty:
Early Restart and Critical Word First

- Don’t wait for full block to be loaded before restarting CPU
  - Early restart—As soon as the requested word of the block arrives, send it to the CPU and let the CPU continue execution
  - Critical Word First—Request the missed word first from memory and send it to the CPU as soon as it arrives; let the CPU continue execution while filling the rest of the words in the block. Also called wrapped fetch and requested word first
- Generally useful only in large blocks,
- Spatial locality a problem; tend to want next sequential word, so not clear if benefit by early restart
3. Reduce Miss Penalty: Non-blocking Caches to reduce stalls on misses

- **Non-blocking cache** or **lockup-free cache** allow data cache to continue to supply cache hits during a miss
  - requires F/E bits on registers or out-of-order execution
  - requires multi-bank memories

- "hit under miss" reduces the effective miss penalty by working during miss vs. ignoring CPU requests

- "hit under multiple miss" or "miss under miss" may further lower the effective miss penalty by overlapping multiple misses
  - Significantly increases the complexity of the cache controller as there can be multiple outstanding memory accesses
  - Requires multiple memory banks (otherwise cannot support)

Value of Hit Under Miss for SPEC

<table>
<thead>
<tr>
<th>Hit Under i Misses</th>
<th>Average Memory Access Time</th>
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<tbody>
<tr>
<td>0</td>
<td>0.2</td>
</tr>
<tr>
<td>1</td>
<td>0.4</td>
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<td>2</td>
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</tr>
<tr>
<td>7</td>
<td>1.6</td>
</tr>
<tr>
<td>8</td>
<td>1.8</td>
</tr>
</tbody>
</table>

- FP programs on average: AMAT = 0.68 -> 0.52 -> 0.34 -> 0.26
- Int programs on average: AMAT = 0.24 -> 0.20 -> 0.19 -> 0.19

8 KB Data Cache, Direct Mapped, 32B block, 16 cycle miss
4: Add a second-level cache

- L2 Equations

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

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

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

- Definitions:
  - Local miss rate—misses in this cache divided by the total number of memory accesses to this cache (Miss rate_{L1})
  - Global miss rate—misses in this cache divided by the total number of memory accesses generated by the CPU (Miss Rate_{L1} \times Miss Rate_{L2})

Comparing Local and Global Miss Rates

- 32 KByte 1st level cache; Increasing 2nd level cache
- Global miss rate close to single level cache rate provided L2 >> L1
- Don’t use local miss rate
- L2 not tied to CPU clock cycle!
- Cost & A.M.A.T.
- Generally Fast Hit Times and fewer misses
- Since hits are few, target miss reduction
Reducing Misses:
Which apply to L2 Cache?

- Reducing Miss Rate
  1. Reduce Misses via Larger Block Size
  2. Reduce Conflict Misses via Higher Associativity
  3. Reducing Conflict Misses via Victim Cache
  4. Reducing Conflict Misses via Pseudo-Associativity
  5. Reducing Misses by HW Prefetching Instr, Data
  6. Reducing Misses by SW Prefetching Data
  7. Reducing Capacity/Conf. Misses by Compiler Optimizations

L2 cache block size &
A.M.A.T.

Relative CPU Time

- 32KB L1, 8 byte path to memory
Reducing Miss Penalty Summary

CPU time = \( IC \times CPI_{cache} + \frac{\text{Memory accesses}}{\text{Instruction}} \times \text{Miss rate} \times \text{Miss penalty} \times \text{Clock cycle time} \)

- **Four techniques**
  - Read priority over write on miss
  - Early Restart and Critical Word First on miss
  - Non-blocking Caches (Hit under Miss, Miss under Miss)
  - Second Level Cache

- **Can be applied recursively to Multilevel Caches**
  - Danger is that time to DRAM will grow with multiple levels in between
  - First attempts at L2 caches can make things worse, since increased worst case is worse

What is the Impact of What You've Learned About Caches?

- **1960-1985**: Speed = \( f(\text{no. operations}) \)
- **1990**
  - Pipelined Execution & Fast Clock Rate
  - Out-of-Order execution
  - Superscalar Instruction Issue
- **1998**: Speed = \( f(\text{non-cached memory accesses}) \)

Superscalar, Out-of-Order machines hide L1 data cache miss (_5 clocks) but not L2 cache miss (_50 clocks)?
## Cache Optimization Summary

<table>
<thead>
<tr>
<th>Technique</th>
<th>MR</th>
<th>MP</th>
<th>HT</th>
<th>Complexity</th>
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<tbody>
<tr>
<td>Larger Block Size</td>
<td>+</td>
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<tr>
<td>Higher Associativity</td>
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<td>Victim Caches</td>
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<td>2</td>
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<td>HW Prefetching of Instr/Data</td>
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<td>Compiler Controlled Prefetching</td>
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<td>Compiler Reduce Misses</td>
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<td>Priority to Read Misses</td>
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<td>Non-Blocking Caches</td>
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<td>Second Level Caches</td>
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