Improving Cache Performance

Average memory-access time = Hit time + Miss rate x Miss penalty (ns or clocks)

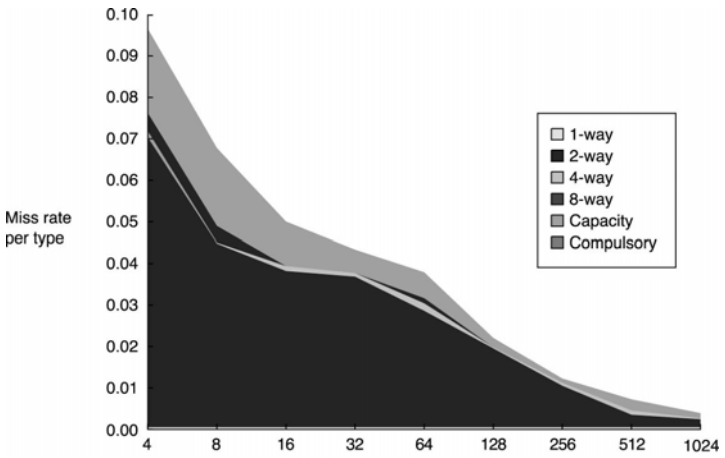
- *1. Reduce the miss rate,*
- 2. Reduce the miss penalty, or
- 3. Reduce the time to hit in the cache.

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*.
  - *Capacity*—If C is the size of the cache (in blocks) and there have been more than C unique cache blocks accessed since this cache was last accessed.
  - *Conflict*—Any miss that is not a compulsory miss or capacity miss must be a byproduct of the cache mapping algorithm. A conflict miss occurs because too many active blocks are mapped to the same cache set.

How To Measure
Misses in infinite cache
Non-compulsory misses in size X fully associative cache
Non-compulsory, non-capacity misses

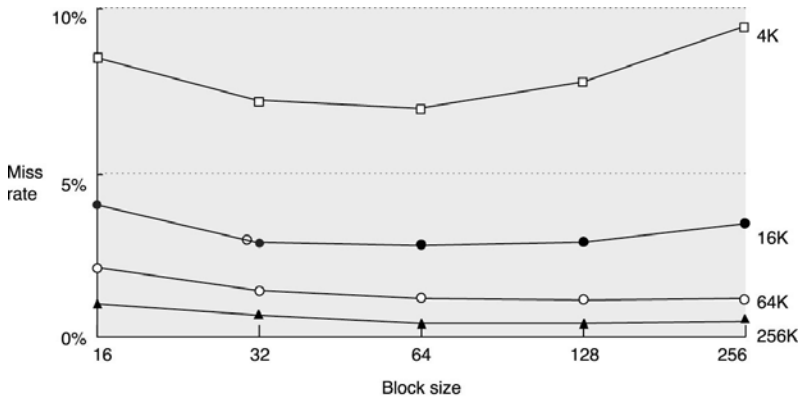
3Cs Absolute Miss Rate



How To Reduce Misses?

- Compulsory Misses?
- Capacity Misses?
- Conflict Misses?
- What can the compiler do?

Reduce Misses via Larger Block Size



- 16K cache, miss penalty for 16-byte block = 42, 32-byte is 44, 64-byte is 48. Miss rates are 3.94, 2.87, and 2.64%. Which gives best performance (lowest AMAT)?

Reduce Misses via Higher Associativity

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

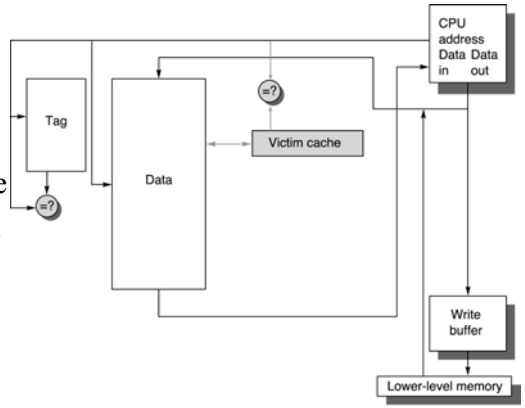
Example: Avg. Memory Access Time vs. Miss Rate

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

AMAT				
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**

Reducing Misses by emulating associativity: Victim Cache

- HR of associative + access time of direct mapped?
- Add buffer to hold data recently discarded from cache
- Jouppi [1990]: 4-entry victim cache removed 20% to 95% of conflicts for a 4 KB direct mapped data cache



Reducing Misses by HW Prefetching of Instruction & Data

- 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 extra memory bandwidth that can be used without penalty

Reducing Misses by SW Prefetching Data

- Data Prefetch
  - Load data into register (HP PA-RISC, IA64, Tera)
  - Cache Prefetch: load into cache (MIPS IV, PowerPC, SPARC)
  - Special prefetching instructions cannot cause faults; a form of speculative execution
- Issuing Prefetch Instructions (including address calculation) takes time
  - Is cost of prefetch issues < savings in reduced misses?

Reducing Misses by Various Compiler Optimizations

- Instructions
  - Reorder procedures in memory so as to reduce misses
  - Profiling to look at conflicts
  - McFarling [1989] reduced cache misses by 75% on 8KB direct mapped cache with 4 byte blocks
- 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 */
int val[SIZE];
int key[SIZE];

/* After */
struct merge {
   int val;
   int key;
};
struct merge merged_array[SIZE];
```

Reducing conflicts between val & key

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

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

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:
  - worst case => $2N^3 + N^2$.
- Idea: compute on BxB submatrix that fits in cache

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;
     };
```

- Capacity Misses from $2N^3 + N^2$ to $2N^3/B + N^2$
- B called *Blocking Factor*
- Conflict Misses Are Not As Easy...

Key Points

$$CPUtime = IC \times \left(CPI_{Execution} + \frac{Memory\ \ accesses}{Instruction} \times \textbf{Miss rate} \times Miss\ \ penalty \right) \times Clock\ \ cycle\ \ time$$

- 3 Cs: Compulsory, Capacity, Conflict Misses
- Reducing Miss Rate
  - 1. Reduce Misses via Larger Block Size
  - 2. Reduce Misses via Higher Associativity
  - 3. Reducing Misses via Victim Cache
  - 4. Reducing Misses by HW Prefetching Instr, Data
  - 5. Reducing Misses by SW Prefetching Data
  - 6. Reducing Misses by Compiler Optimizations
- Remember danger of concentrating on just one parameter when evaluating performance
- Next: reducing Miss penalty

Improving Cache Performance

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

Reducing Miss Penalty: Read Priority over Write on Miss

- The easiest way to resolve RAW hazards (and other ordering issues) between loads and stores is to send them all to memory in instruction order.
- If always wait for write buffer to empty might increase read miss penalty by 50%
- Check write buffer contents before read; if no conflicts, let the memory access continue
- Write Back Caches?
  - Read miss may require write of 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 stalls less since it can restart as soon as read completes

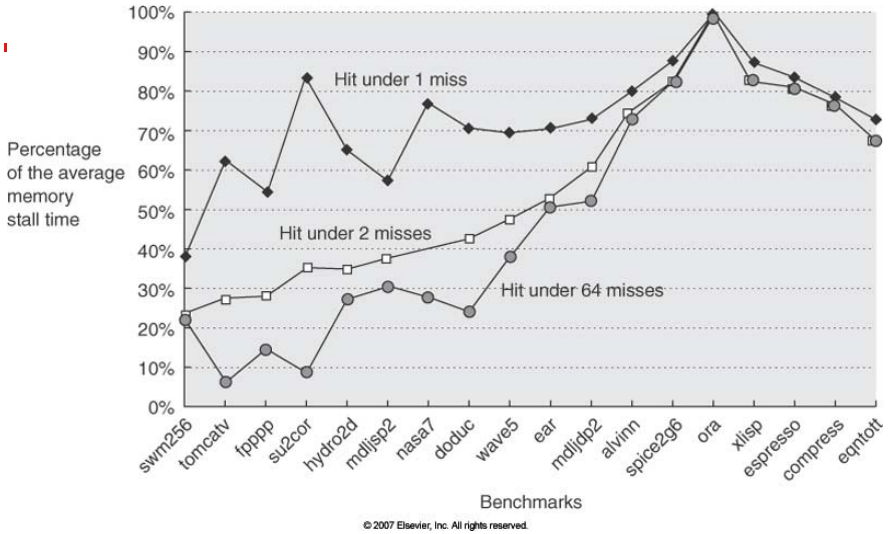
Early Restart and Critical Word First

- 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*
- Most useful with large blocks,
- Spatial locality a problem; often we want the next sequential word soon, so not always a benefit (early restart).

Non-blocking Caches to reduce stalls on misses

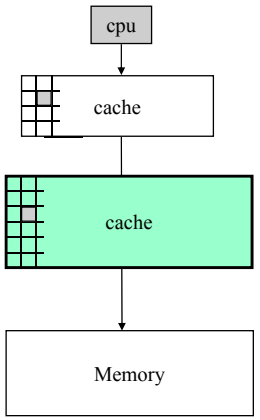
- *Non-blocking cache* (or *lockup-free cache)* allowd the data cache to continue to supply cache hits during a miss
- "*hit under miss*" reduces the effective miss penalty by being helpful during a miss instead of ignoring the requests of the CPU
- "*hit under multiple miss*" or "*miss under miss*" can 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
- assumes "stall on use" not "stall on miss" which works naturally with dynamic scheduling, but can also work with static.

Value of Hit Under Miss for SPEC



But...

- The primary way to reduce miss penalty…



Miss Penalty Reduction: Second Level Cache

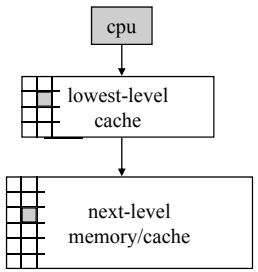
- L2 Equations

  $AMAT = Hit\ Time_{L1} + Miss\ Rate_{L1} \times Miss\ Penalty_{L1}$

  $Miss\ Penalty_{L1} = Hit\ Time_{L2} + Miss\ Rate_{L2} \times Miss\ Penalty_{L2}$

  $AMAT = Hit\ Time_{L1} + Miss\ Rate_{L1} \times (Hit\ Time_{L2} + Miss\ Rate_{L2} + Miss\ Penalty_{L2})$

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



Multi-level Caches, cont.

- L1 cache local miss rate 10%, L2 local miss rate 40%. What are the global miss rates?
- L1 highest priority is fast hit time. L2 typically low miss rate.
- Design L1 and L2 caches in concert.
- Property of inclusion -- if it is in L1 cache, it is guaranteed to be in the L2 cache -- simplifies design of consistent caches.
- L2 cache can have different associativity (good idea?) or block size (good idea?) than L1 cache.
- These principles can continue to be applied recursively to Multilevel Caches
  - Danger is that time to DRAM will grow with multiple levels in between

Reducing Miss Penalty Summary

- Four techniques
  - Read priority over write on miss
  - Early Restart and Critical Word First on miss
  - Non-blocking Caches (Hit Under Miss)
  - Multi-level Caches

Review: Improving Cache Performance

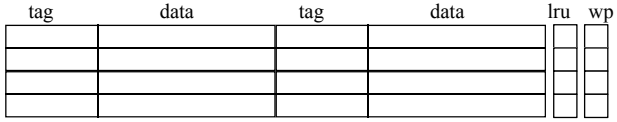
1. Reduce the miss rate,
2. Reduce the miss penalty, or
3. *Reduce the time to hit in the cache.*

Fast Hit times via Small and Simple Caches

- This is why Alpha 21164 has 8KB Instruction and 8KB data cache + 96KB second level cache
- I and D caches used to be typically Direct Mapped, on chip

DM Hit Time + Associative Hit Rate -> Way Prediction

- Add bits (?) to each cache line to predict which way is going to hit.
- How is that going to help?
  - Read one tag & compare
  - Speculatively read data from that one block
- Next cycle
  - Read other tags and compare
- Pentium 4

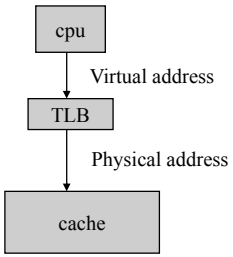


Fast hits by Avoiding Address Translation: Virtual Cache

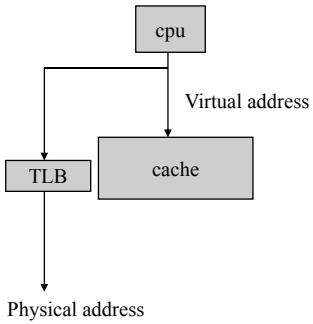
- Send virtual address to cache? Called *Virtually Addressed Cache* or just *Virtual Cache* vs. *Physical Cache*
  - Every time process is switched logically must flush the cache; otherwise get false hits
    - Cost is time to flush + "compulsory" misses from empty cache
  - Dealing with *aliases* (sometimes called *synonyms*); Two different virtual addresses map to same physical address
  - I/O must interact with cache…
- Solution to aliases
  - HW that guarantees that every cache block has unique physical address
  - SW guarantee : lower n bits must have same address; as long as covers index field & direct mapped, they must be unique; called *page coloring*
- Solution to cache flush
  - Add *process identifier tag* that identifies process as well as address within process: can't get a hit if wrong process

Virtual Cache

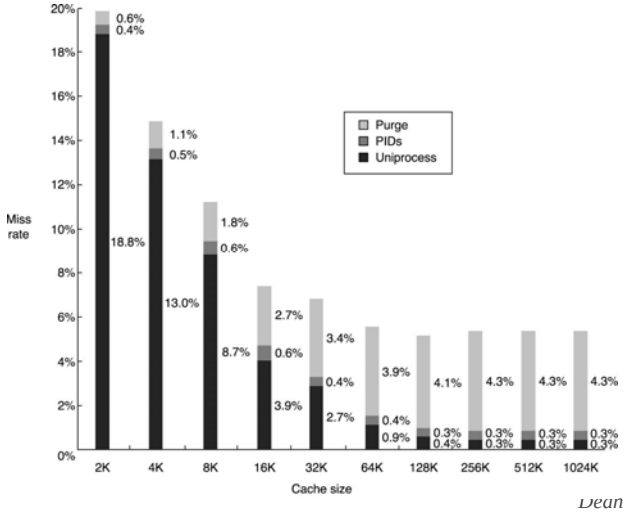
- Physical Cache



Virtual Cache



Avoiding Translation: Process ID impact



Cache Bandwidth: Trace Caches

- Fetch Bottleneck – Cannot execute instructions faster than you can fetch them into the processor.
- Cannot typically fetch more than about one taken branch per cycle, at best (why? Why one *taken* branch?)
- Trace cache is an instruction cache that stores instructions in *dynamic execution order* rather than program/address order.
- Implemented on the Pentium 4

Trace Cache

Cache Optimization Summary

Technique	*MR*	*MP*	*HT*	*Complexity*
Larger Block Size				
Higher Associativity				
Victim Caches				
HW Prefetching of Instr/Data				
Compiler Controlled Prefetching				
Compiler Reduce Misses				
Priority to Read Misses				
Early Restart & Critical Word 1st				
Non-Blocking Caches				
Second Level Caches				
Small & Simple Caches				
Way Prediction				
Avoiding Address Translation				
Trace Cache?				

Cache Research at UCSD

- Hardware prefetching of complex data structures (e.g., pointer chasing)
- Fetch Target Buffer
  - Let branch predictor run ahead of fetch engine
- Runtime identification of cache conflict misses
- Speculative Precomputation (helper thread prefetching)
  - Spawn threads at runtime to calculate addresses of delinquent (problematic) loads and prefetch → creates prefetcher from application code.
- Code Layout to Reduce Icache Conflict Misses
  - Also, for multithreaded processors
- Code Layout to Reduce Dcache Conflict Misses
  - Also, for multithreaded processors

Cache Research at UCSD, cont.

- Event-driven compilation – while main thread runs, hw monitors identify problematic loads, then fork new compilation thread (on SMT or CMP) to alter code.
  - Dynamic value specialization
  - Inline software prefetching
  - Helper thread prefetching (speculative precomputation)
- Software Data Spreading
  - Insert migration calls in loops with large data sets, spreading the data over multiple private caches.
- Inter-core Prefetching
  - Prefetch thread runs ahead of main thread, but in another core. After an interval, they swap cores. The main thread finds all of its data preloaded into the new cache, and the prefetcher starts prefilling the next cache.