Last time in Lecture 6

- Dynamic RAM (DRAM) is main form of main memory storage in use today
  - Holds values on small capacitors, need refreshing (hence dynamic)
  - Slow multi-step access: precharge, read row, read column
- Static RAM (SRAM) is faster but more expensive
  - Used to build on-chip memory for caches
- Cache holds small set of values in fast memory (SRAM) close to processor
  - Need to develop search scheme to find values in cache, and replacement policy to make space for newly accessed locations
- Caches exploit two forms of predictability in memory reference streams
  - Temporal locality, same location likely to be accessed again soon
  - Spatial locality, neighboring location likely to be accessed soon
CPU-Cache Interaction
(5-stage pipeline)

Cache Refill Data from Lower Levels of Memory Hierarchy

Stall entire CPU on data cache miss

To Memory Control
Improving Cache Performance

Average memory access time =
\[ \text{Hit time} + \text{Miss rate} \times \text{Miss penalty} \]

To improve performance:
• reduce the hit time
• reduce the miss rate
• reduce the miss penalty

What is the simplest design strategy?

Biggest cache that doesn’t increase hit time past 1-2 cycles
(approx 8-32KB in modern technology)
[ design issues more complex with out-of-order superscalar processors ]
Serial-versus-Parallel Cache and Memory access

α is HIT RATIO: Fraction of references in cache
1 - α is MISS RATIO: Remaining references

Average access time for serial search: \( t_{\text{cache}} + (1 - \alpha) \ t_{\text{mem}} \)

Average access time for parallel search: \( \alpha \ t_{\text{cache}} + (1 - \alpha) \ t_{\text{mem}} \)

- Savings are usually small, \( t_{\text{mem}} >> t_{\text{cache}} \), hit ratio \( \alpha \) high
- High bandwidth required for memory path
- Complexity of handling parallel paths can slow \( t_{\text{cache}} \)
Causes for Cache Misses

- **Compulsory:** first-reference to a block *a.k.a.* cold start misses
  - misses that would occur even with infinite cache

- **Capacity:** cache is too small to hold all data needed by the program
  - misses that would occur even under perfect replacement policy

- **Conflict:** misses that occur because of collisions due to block-placement strategy
  - misses that would not occur with full associativity
Effect of Cache Parameters on Performance

- Larger cache size
  + reduces capacity and conflict misses
  - hit time will increase

- Higher associativity
  + reduces conflict misses
  - may increase hit time

- Larger block size
  + reduces compulsory and capacity (reload) misses
  - increases conflict misses and miss penalty
Write Policy Choices

• Cache hit:
  – *write through*: write both cache & memory
    » Generally higher traffic but simpler pipeline & cache design
  – *write back*: write cache only, memory is written only when the entry is evicted
    » A dirty bit per block further reduces write-back traffic
    » Must handle 0, 1, or 2 accesses to memory for each load/store

• Cache miss:
  – *no write allocate*: only write to main memory
  – *write allocate* (*aka fetch on write*): fetch into cache

• Common combinations:
  – write through and no write allocate
  – write back with write allocate
Write Performance

Tag Index Block Offset

V t k b

HIT

2^k lines

Data Word or Byte

Data

WE
Reducing Write Hit Time

Problem: Writes take two cycles in memory stage, one cycle for tag check plus one cycle for data write if hit

Solutions:

• Design data RAM that can perform read and write in one cycle, restore old value after tag miss

• Fully-associative (CAM Tag) caches: Word line only enabled if hit

• Pipelined writes: Hold write data for store in single buffer ahead of cache, write cache data during next store’s tag check
Pipelining Cache Writes

Address and Store Data From CPU

Tag → Index

Store Data

Delayed Write Addr.

Delayed Write Data

Tags

Load/Store

Data

1 0

Hit?

Load Data to CPU

Data from a store hit written into data portion of cache during tag access of subsequent store
Write Buffer to Reduce Read Miss Penalty

Problem: Write buffer may hold updated value of location needed by a read miss

Simple scheme: on a read miss, wait for the write buffer to go empty

Faster scheme: Check write buffer addresses against read miss addresses, if no match, allow read miss to go ahead of writes, else, return value in write buffer

Processor is not stalled on writes, and read misses can go ahead of write to main memory

Evicted dirty lines for writeback cache

OR

All writes in writethrough cache
Block-level Optimizations

• Tags are too large, i.e., too much overhead
  – Simple solution: Larger blocks, but miss penalty could be large.
• Sub-block placement (aka sector cache)
  – A valid bit added to units smaller than full block, called sub-blocks
  – Only read a sub-block on a miss
  – *If a tag matches, is the word in the cache?*
Multilevel Caches

Problem: A memory cannot be large and fast
Solution: Increasing sizes of cache at each level

![Diagram of CPU, L1$, L2$, DRAM]

Local miss rate = misses in cache / accesses to cache
Global miss rate = misses in cache / CPU memory accesses
Misses per instruction = misses in cache / number of instructions
Presence of L2 influences L1 design

• Use smaller L1 if there is also L2
  – Trade increased L1 miss rate for reduced L1 hit time and reduced L1 miss penalty
  – Reduces average access energy

• Use simpler write-through L1 with on-chip L2
  – Write-back L2 cache absorbs write traffic, doesn’t go off-chip
  – At most one L1 miss request per L1 access (no dirty victim write back) simplifies pipeline control
  – Simplifies coherence issues
  – Simplifies error recovery in L1 (can use just parity bits in L1 and reload from L2 when parity error detected on L1 read)
Inclusion Policy

• Inclusive multilevel cache:
  – Inner cache holds copies of data in outer cache
  – External coherence snoop access need only check outer cache

• Exclusive multilevel caches:
  – Inner cache may hold data not in outer cache
  – Swap lines between inner/outer caches on miss
  – Used in AMD Athlon with 64KB primary and 256KB secondary cache

Why choose one type or the other?
Itanium-2 On-Chip Caches
(Intel/HP, 2002)

**Level 1:** 16KB, 4-way s.a., 64B line, quad-port (2 load+2 store), single cycle latency

**Level 2:** 256KB, 4-way s.a., 128B line, quad-port (4 load or 4 store), five cycle latency

**Level 3:** 3MB, 12-way s.a., 128B line, single 32B port, twelve cycle latency
Power 7 On-Chip Caches [IBM 2009]

- 32KB L1 I$ per core
- 32KB L1 D$ per core
- 3-cycle latency

- 256KB Unified L2$ per core
- 8-cycle latency

- 32MB Unified Shared L3$
- Embedded DRAM
- 25-cycle latency to local slice
CS152 Administrivia
Prefetching

• Speculate on future instruction and data accesses and fetch them into cache(s)
  – Instruction accesses easier to predict than data accesses

• Varieties of prefetching
  – Hardware prefetching
  – Software prefetching
  – Mixed schemes

• What types of misses does prefetching affect?
Issues in Prefetching

- Usefulness – should produce hits
- Timeliness – not late and not too early
- Cache and bandwidth pollution
Hardware Instruction Prefetching

Instruction prefetch in Alpha AXP 21064

- Fetch two blocks on a miss; the requested block (i) and the next consecutive block (i+1)
- Requested block placed in cache, and next block in instruction stream buffer
- If miss in cache but hit in stream buffer, move stream buffer block into cache and prefetch next block (i+2)
Hardware Data Prefetching

• Prefetch-on-miss:
  – Prefetch \( b + 1 \) upon miss on \( b \)

• One Block Lookahead (OBL) scheme
  – Initiate prefetch for block \( b + 1 \) when block \( b \) is accessed
  – *Why is this different from doubling block size?*
  – Can extend to N-block lookahead

• Strided prefetch
  – If observe sequence of accesses to block \( b, b+N, b+2N \), then prefetch \( b+3N \) etc.

**Example:** IBM Power 5 [2003] supports eight independent streams of strided prefetch per processor, prefetching 12 lines ahead of current access
Software Prefetching

```c
for(i=0; i < N; i++) {
    prefetch( &a[i+1] );
    prefetch( &b[i+1] );
    SUM = SUM + a[i] * b[i];
}
```
Software Prefetching Issues

• Timing is the biggest issue, not predictability
  – If you prefetch very close to when the data is required, you might be too late
  – Prefetch too early, cause pollution
  – Estimate how long it will take for the data to come into L1, so we can set $P$ appropriately
  – Why is this hard to do?

```c
for(i=0; i < N; i++) {
    prefetch( &a[i + P] );
    prefetch( &b[i + P] );
    SUM = SUM + a[i] * b[i];
}
```

Must consider cost of prefetch instructions
Compiler Optimizations

• Restructuring code affects the data block access sequence
  – Group data accesses together to improve spatial locality
  – Re-order data accesses to improve temporal locality

• Prevent data from entering the cache
  – Useful for variables that will only be accessed once before being replaced
  – Needs mechanism for software to tell hardware not to cache data ("no-allocate" instruction hints or page table bits)

• Kill data that will never be used again
  – Streaming data exploits spatial locality but not temporal locality
  – Replace into dead cache locations
Loop Interchange

for (j=0; j < N; j++) {
    for (i=0; i < M; i++) {
        x[i][j] = 2 * x[i][j];
    }
}

for (i=0; i < M; i++) {
    for (j=0; j < N; j++) {
        x[i][j] = 2 * x[i][j];
    }
}

What type of locality does this improve?
Loop Fusion

for (i=0; i < N; i++)
    a[i] = b[i] * c[i];

for (i=0; i < N; i++)
    d[i] = a[i] * c[i];

for (i=0; i < N; i++)
{
    a[i] = b[i] * c[i];
    d[i] = a[i] * c[i];
}

What type of locality does this improve?
Matrix Multiply, Naïve Code

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

Matrix Access Diagram:
- **Not touched**
- **Old access**
- **New access**

February 9, 2011
CS152, Spring 2011
Matrix Multiply with Cache Tiling

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

What type of locality does this improve?
Acknowledgements

• These slides contain material developed and copyright by:
  – Arvind (MIT)
  – Krste Asanovic (MIT/UCB)
  – Joel Emer (Intel/MIT)
  – James Hoe (CMU)
  – John Kubiatowicz (UCB)
  – David Patterson (UCB)

• MIT material derived from course 6.823
• UCB material derived from course CS252