Chapter Seven

CACHE MEMORY
AND VIRTUAL MEMORY

Memories: Review

• SRAM:
  - value is stored on a pair of inverting gates
  - very fast but takes up more space than DRAM (4 to 6 transistors)

• DRAM:
  - value is stored as a charge on capacitor (must be refreshed)
  - very small but slower than SRAM (factor of 5 to 10)

Exploiting Memory Hierarchy

Users want large and fast memories!

1997
- SRAM access times are 2 - 25 ns at cost of $100 to $250 per Mbyte.
- DRAM access times are 50 - 120 ns at cost of $5 to $10 per Mbyte.
- Disk access times are 10 to 20 million ns at cost of $0.10 to $0.20 per Mbyte.

2005
- SRAM access times are 1.25 ns at cost of $1000 per Gbyte.
- DRAM access times are 2.5 ns at cost of $100 per Gbyte.
- Disk access times are 200,000 ns at cost of $1 per Gbyte.

Try and give it to them anyway - build a memory hierarchy

Increasing distance from CPU in access time.
Locality

- A principle that makes having a memory hierarchy a good idea
- If an item is referenced, temporal locality: it will tend to be referenced again soon
  spatial locality: nearby items will tend to be referenced soon.

Why does code have locality?

- Our initial focus: two level model (upper, lower)
  - block: minimum unit of data
  - hit: data requested is in the upper level
  - miss: data requested is not in the upper level

Cache

- Two issues:
  - How do we know if a data item is in the cache?
  - If it is, how do we find it?
- Our first example:
  - block size is one word of data
  - "direct mapped"

  For each item of data at the lower level, there is exactly one location in the cache where it might be.
  e.g., lots of items at the lower level share locations in the upper level

Direct Mapped Cache

- Mapping: address is modulo the number of blocks in the cache
For MIPS:

What kind of locality are we taking advantage of?

Direct Mapped Cache

• Taking advantage of spatial locality:

Direct Mapped Cache

• For MIPS:

What kind of locality are we taking advantage of?
Hits vs. Misses

- Read hits
  - this is what we want!
- Read misses
  - stall the CPU, fetch block from memory, deliver to cache, restart
- Write hits:
  - can replace data in cache and memory (write-through)
- Write misses:
  - write the data only into the cache (write-back the cache later)

Hardware Issues

- Make reading multiple words easier by using banks of memory
- It can get a lot more complicated...

Performance

- Increasing the block size tends to decrease miss rate:
- Use split caches because there is more spatial locality in code:

<table>
<thead>
<tr>
<th>Program</th>
<th>Block size in words</th>
<th>Instruction miss rate</th>
<th>Data miss rate</th>
<th>Effective combined miss rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>gcc</td>
<td>1</td>
<td>1.2%</td>
<td>1.3%</td>
<td>1.2%</td>
</tr>
<tr>
<td>spice</td>
<td>4</td>
<td>0.3%</td>
<td>0.3%</td>
<td>0.4%</td>
</tr>
</tbody>
</table>
**Performance**

- Simplified model:
  \[
  \text{execution time} = (\text{execution cycles} + \text{stall cycles}) \times \text{cycle time}
  \]
  stall cycles = \( \# \) of instructions \( \times \) miss ratio \( \times \) miss penalty

- Two ways of improving performance:
  - decreasing the miss ratio
  - decreasing the miss penalty

What happens if we increase block size?

**Decreasing miss ratio with associativity**

- Compared to direct mapped, give a series of references that:
  - results in a lower miss ratio

  - assuming we use the “least recently used” replacement strategy

**An implementation**

- Diagram showing an implementation of a cache with various associativities.
Performance

![Graph showing Miss Rate (%)](image)

- **Associativity**
  - 1-way
  - 2-way
  - 4-way
  - 8-way

- **Cache Size (kbyte)**
  - 1
  - 2
  - 4
  - 8
  - 16
  - 32
  - 64
  - 128

- **Decreasing miss penalty with multilevel caches**
  - Add a second level cache:
    - often primary cache is on the same chip as the processor
    - use SRAMs to add another cache above primary memory (DRAM)
    - miss penalty goes down if data is in 2nd level cache

  - Example:
    - CPI of 1.0 on a 500MHz machine with a 5% miss rate, 200ns DRAM access
    - Adding 2nd level cache with 20ns access time decreases miss rate to 2%

  - Using multilevel caches:
    - try and optimize the hit time on the 1st level cache
    - try and optimize the miss rate on the 2nd level cache

Virtual Memory

- **Main memory can act as a cache for the secondary storage (disk)**

- **Advantages:**
  - illusion of having more physical memory
  - program relocation
  - protection
Pages: virtual memory blocks

- Page faults: the data is not in memory, retrieve it from disk
  - huge miss penalty, thus pages should be fairly large (e.g., 4KB)
  - reducing page faults is important (LRU is worth the price)
  - can handle the faults in software instead of hardware
  - using write-through is too expensive so we use writeback

Page Tables

Page Tables
Making Address Translation Fast

- A cache for address translations: translation lookaside buffer

TLBs and caches

Modern Systems

- Very complicated memory systems:

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Intel Pentium Pro</th>
<th>PowerPC 604</th>
</tr>
</thead>
<tbody>
<tr>
<td>Instruction TLB</td>
<td>32 entries</td>
<td>128 entries</td>
</tr>
<tr>
<td>Data TLB</td>
<td>64 entries</td>
<td>128 entries</td>
</tr>
<tr>
<td>TLB misses</td>
<td>Handled in hardware</td>
<td>Handled in hardware</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Intel Pentium Pro</th>
<th>PowerPC 604</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cache size</td>
<td>8 KB each for instructions/data</td>
<td>16 KB each for instructions/data</td>
</tr>
<tr>
<td>Cache associativity</td>
<td>Four-way set associative</td>
<td>Four-way set associative</td>
</tr>
<tr>
<td>Replacement</td>
<td>Approximated LRU replacement</td>
<td>LRU replacement</td>
</tr>
<tr>
<td>Block size</td>
<td>32 bytes</td>
<td>32 bytes</td>
</tr>
<tr>
<td>Write policy</td>
<td>Write-back or write-through</td>
<td>Write-back or write-through</td>
</tr>
</tbody>
</table>
• Processor speeds continue to increase very fast
  – much faster than either DRAM or disk access times
• Design challenge: dealing with this growing disparity
• Trends:
  – synchronous SRAMs (provide a burst of data)
  – redesign DRAM chips to provide higher bandwidth or processing
  – restructure code to increase locality
  – use prefetching (make cache visible to ISA)