Caching
Key Point

• What are
  • Cache lines
  • Tags
  • Index
  • offset

• How do we find data in the cache?
• How do we tell if it’s the right data?
• What decisions do we need to make in designing a cache?
  • What are possible caching policies?
The Memory Hierarchy

• There can be many caches stacked on top of each other
• if you miss in one you try in the “lower level cache”
  Lower level, mean higher number
• There can also be separate caches for data and instructions. Or the cache can be “unified”
• to wit:
  • the L1 data cache (d-cache) is the one nearest processor. It corresponds to the “data memory” block in our pipeline diagrams
  • the L1 instruction cache (i-cache) corresponds to the “instruction memory” block in our pipeline diagrams.
  • The L2 sits underneath the L1s.
  • There is often an L3 in modern systems.
Typical Cache Hierarchy

- Fetch/L1 Icache 16KB
- Decode
- EX
- Mem L1 Dcache 16KB
- Write back

Unified L2 8MB

Unified L3 32MB

DRAM Many GBs
The Memory Hierarchy and the ISA

• The details of the memory hierarchy are not part of the ISA
  • These are implementations detail.
  • Caches are completely transparent to the processor.

• The ISA...
  • Provides a notion of main memory, and the size of the addresses that refer to it (in our case 32 bits)
  • Provides load and store instructions to access memory.

• The memory hierarchy is all about making main memory fast.
Basic Problems in Caching

- A cache holds a small fraction of all the cache lines, yet the cache itself may be quite large (i.e., it might contain 1000s of lines)
- Where do we look for our data?
- How do we tell if we’ve found it and whether it’s any good?
The Cache Line

• Caches operate on “lines”
• Caches lines are a power of 2 in size
  • They contain multiple words of memory.
• Usually between 16 and 128 bytes
Basic Cache Organization

- Anatomy of a cache line entry
  - Tag -- The high order bits of the address
  - Data -- The program’s data
  - Dirty bit -- Has the cache line been modified?

- Anatomy of an address
  - Index -- bits that determine the lines possible location
  - Offset -- which byte within the line (low-order bits)
  - Tag -- everything else (the high-order bits)

- Note that the index bits, combined with the tag bits, uniquely identify one cache line’s worth of memory
Cache line size

• How big should a cache line be?
• Why is bigger better?
• Why is smaller better?
Cache line size

• How big should a cache line be?
• Why is bigger better?
  • Exploits more spatial locality.
  • Large cache lines effectively *prefetch* data that we have not explicitly asked for.
• Why is smaller better?
  • Focuses on temporal locality.
  • If there is little spatial locality, large cache lines waste space and bandwidth.
• In practice 32-64 bytes is good for L1 caches were space is scarce and latency is important.
• Lower levels use 128-256 bytes.
Cache Geometry Calculations

- Addresses break down into: tag, index, and offset.
- How they break down depends on the “cache geometry”

- Cache lines = L
- Cache line size = B
- Address length = A (32 bits in our case)

- Index bits = log₂(L)
- Offset bits = log₂(B)
- Tag bits = A - (index bits + offset bits)
Practice

• 1024 cache lines. 32 Bytes per line.
• Index bits:
• Tag bits:
• off set bits:
Practice

- 1024 cache lines. 32 Bytes per line.
- Index bits: 10
- Tag bits:
- Offset bits:
Practice

• 1024 cache lines. 32 Bytes per line.
• Index bits: 10
• Tag bits:
• off set bits: 5
Practice

• 1024 cache lines. 32 Bytes per line.
• Index bits: 10
• Tag bits: 17
• off set bits: 5
Practice

- 32KB cache.
- 64byte lines.

- Index
- Offset
- Tag
Practice

• 32KB cache.
• 64byte lines.

• Index
• Offset
• Tag
Practice

• 32KB cache.
• 64byte lines.

• Index 9
• Offset
• Tag 17
Practice

- 32KB cache.
- 64byte lines.

- Index 9
- Offset 6
- Tag 17
Reading from a cache

• Determine where in the cache, the data could be
• If the data is there (i.e., is it hit?), return it
• Otherwise (a miss)
  • Retrieve the data from the lower down the cache hierarchy.
  • Choose a line to evict to make room for the new line
    • Is it dirty? Write it back.
    • Otherwise, just replace it, and return the value

• The choice of which line to evict depends on the “Replacement policy”
Hit or Miss?

- Use the index to determine where in the cache, the data might be.
- Read the tag at that location, and compare it to the tag bits in the requested address.
- If they match (and the data is valid), it’s a hit.
- Otherwise, a miss.
On a Miss: Making Room

- We need space in the cache to hold the data we want to access.
- We will need to **evict** the cache line at this index.
  - If it’s dirty, we need to **write it back**
  - Otherwise (it’s clean), we can just overwrite it.
Writing To the Cache (simple version)

- Determine where in the cache, the data could be
- If the data is there (i.e., is it hit?), update it
- Possibly forward the request down the hierarchy
- Otherwise
  - Retrieve the data from the lower down the cache hierarchy (why?)
  - Option 1: choose a line to evict
    - Is it dirty? Write it back.
    - Otherwise, just replace it, and update it.
  - Option 2: Forward the write request down the hierarchy
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Write back policy
Replacement policy
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  • Retrieve the data from the lower down the cache hierarchy (why?)
  • **Option 1:** choose a line to evict
    • Is it dirty? Write it back.
    • Otherwise, just replace it, and update it.
  • **Option 2:** Forward the write request down the hierarchy

Write allocation policy
Write Through vs. Write Back

• When we perform a write, should we just update this cache, or should we also forward the write to the next lower cache?

• If we do not forward the write, the cache is “Write back”, since the data must be written back when it’s evicted (i.e., the line can be dirty)

• If we do forward the write, the cache is “write through.” In this case, a cache line is never dirty.

• Write back advantages

• Write through advantages
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- Write back advantages
- Write through advantages

No write back required on eviction.
Write Through vs. Write Back

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• If we do forward the write, the cache is “write through.” In this case, a cache line is never dirty.
• Write back advantages
  Fewer writes farther down the hierarchy. Less bandwidth. Faster writes
• Write through advantages
  No write back required on eviction.
Write Allocate/No-write allocate

- On a write miss, we don’t actually need the data, we can just forward the write request
- If the cache allocates cache lines on a write miss, it is write allocate, otherwise, it is no write allocate.
- Write Allocate advantages

- No-write allocate advantages

  Fewer spurious evictions. If the data is not read in the near future, the eviction is a waste.
Write Allocate/No-write allocate

- On a write miss, we don’t actually need the data, we can just forward the write request
- If the cache allocates cache lines on a write miss, it is *write allocate*, otherwise, it is *no write allocate*.
- Write Allocate advantages
  
Exploits temporal locality. Data written will likely be read soon, and that read will be faster.

- No-write allocate advantages

  Fewer spurious evictions. If the data is not read in the near future, the eviction is a waste.
Dealing the Interference

• By bad luck or pathological happenstance a particular line in the cache may be highly contended.
• How can we deal with this?
Interfering Code.

int foo[129]; // 4*129 = 516 bytes
int bar[129]; // Assume the compiler
aligns these at 512 byte boundaries

while(1) {
  for (i = 0; i < 129; i++) {
    s += foo[i] * bar[i];
  }
}

- Assume a 1KB (0x400 byte) cache.
- Foo and Bar map into exactly the same part of the cache
- Is the miss rate for this code going to be high or low?
- What would we like the miss rate to be?
  - Foo and Bar should both (almost) fit in the cache!
Associativity

• (set) Associativity means providing more than one place for a cache line to live.
• The level of associativity is the number of possible locations
  • 2-way set associative
  • 4-way set associative
• One group of lines corresponds to each index
  • it is called a “set”
• Each line in a set is called a “way”
### Associativity

<table>
<thead>
<tr>
<th>Subject</th>
<th>dirty</th>
<th>Tag</th>
<th>Data</th>
</tr>
</thead>
<tbody>
<tr>
<td>Set 0</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Set 1</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Set 2</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Set 3</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The diagram illustrates the organization of data in an associative memory. Each set contains three elements: dirty, Tag, and Data. There are two ways, Way 0 and Way 1, connecting these sets.
New Cache Geometry Calculations

- Addresses break down into: tag, index, and offset.
- How they break down depends on the “cache geometry”

- Cache lines = \( L \)
- Cache line size = \( B \)
- Address length = \( A \) (32 bits in our case)
- Associativity = \( W \)

- Index bits = \( \log_2(L/W) \)
- Offset bits = \( \log_2(B) \)
- Tag bits = \( A - (\text{index bits} + \text{offset bits}) \)
Practice

• 32KB, 2048 Lines, 4-way associative.

• Line size:
• Sets:
• Index bits:
• Tag bits:
• Offset bits:
Practice

- 32KB, 2048 Lines, 4-way associative.
- Line size: 16B
- Sets:
- Index bits:
- Tag bits:
- Offset bits:
Practice

- 32KB, 2048 Lines, 4-way associative.

- Line size: 16B
- Sets: 512
- Index bits:
- Tag bits:
- Offset bits:
Practice

• 32KB, 2048 Lines, 4-way associative.

• Line size: 16B
• Sets: 512
• Index bits: 9
• Tag bits:
• Offset bits:
Practice

• 32KB, 2048 Lines, 4-way associative.

• Line size: 16B
• Sets: 512
• Index bits: 9
• Tag bits:
• Offset bits: 4
Practice

• 32KB, 2048 Lines, 4-way associative.

• Line size: 16B
• Sets: 512
• Index bits: 9
• Tag bits: 19
• Offset bits: 4
Fully Associative and Direct Mapped Caches

• At one extreme, a cache can have one, large set.
  • The cache is then fully associative
• At the other, it can have one cache line per set
  • Then it is direct mapped
Eviction in Associative caches

• We must choose which line in a set to evict if we have associativity
• How we make the choice is called the cache eviction policy
  • Random -- always a choice worth considering.
  • Least recently used (LRU) -- evict the line that was last used the longest time ago.
  • Prefer clean -- try to evict clean lines to avoid the write back.
  • Farthest future use -- evict the line whose next access is farthest in the future. This is provably optimal. It is also impossible to implement.
The Cost of Associativity

- Increased associativity requires multiple tag checks
  - N-Way associativity requires N parallel comparators
  - This is expensive in hardware and potentially slow.
- This limits associativity L1 caches to 2-8.
- Larger, slower caches can be more associative.
- Example: Nehalem
  - 8-way L1
  - 16-way L2 and L3.
- Core 2’s L2 was 24-way