Cache Memories

CS351: Systems Programming
Day 14: Oct. 06, 2022

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Slides adapted from Bryant and O’Hallaron

(We’re halfway through the course)
Today

- Cache memory organization and operation
- Performance impact of caches
  - The memory mountain
  - Rearranging loops to improve spatial locality
  - Using blocking to improve temporal locality
Example Memory Hierarchy

- **L0:** CPU registers hold words retrieved from the L1 cache.
- **L1:** L1 cache holds cache lines retrieved from the L2 cache.
- **L2:** L2 cache holds cache lines retrieved from L3 cache.
- **L3:** L3 cache holds cache lines retrieved from main memory.
- **L4:** Main memory holds disk blocks retrieved from local disks.
- **L5:** Local disks hold files retrieved from disks on remote servers.
- **L6:** Remote secondary storage (e.g., Web servers)

Smaller, faster, and costlier (per byte) storage devices

Larger, slower, and cheaper (per byte) storage devices
General Cache Concept

Data is copied in block-sized transfer units

Smaller, faster, more expensive memory caches a subset of the blocks

Larger, slower, cheaper memory viewed as partitioned into “blocks”
Cache Memories

- **Cache memories** are small, fast SRAM-based memories managed automatically in hardware
  - Hold frequently accessed blocks of main memory
- **CPU looks first for data in cache**
- **Typical system structure:**

![Diagram of typical system structure]
General Cache Organization (S, E, B)

- **E** = \(2^e\) lines per set
- **S** = \(2^s\) sets
- **B** = \(2^b\) bytes per cache block (the data)

**Cache size:**
\[C = S \times E \times B\text{ data bytes}\]
Cache Read

\[ E = 2^e \text{ lines per set} \]

\[ S = 2^s \text{ sets} \]

- Locate set
- Check if any line in set has matching tag
- Yes + line valid: hit
- Locate data starting at offset

Address of word:

\[ \text{tag} \quad \text{set index} \quad \text{block offset} \]

Data begins at this offset

\[ B = 2^b \text{ bytes per cache block (the data)} \]

Valid bit
Example: Direct Mapped Cache (E = 1)

Direct mapped: One line per set
Assume: cache block size 8 bytes

\[ S = 2^s \text{ sets} \]

Address of int:
\[
\begin{array}{c|c|c}
\text{t bits} & 0 & 1 & 00 \\
\end{array}
\]

find set
Example: Direct Mapped Cache (E = 1)

Direct mapped: One line per set
Assume: cache block size 8 bytes

Address of int:

v

tag
0 1 2 3 4 5 6 7

valid? + match: assume yes = hit

block offset
Example: Direct Mapped Cache $(E = 1)$

Direct mapped: One line per set
Assume: cache block size 8 bytes

If tag doesn’t match: old line is evicted and replaced
Direct-Mapped Cache Simulation

M=16 bytes (4-bit addresses), B=2 bytes/block, S=4 sets, E=1 Blocks/set

Address trace (reads, one byte per read):

- 0: [0000₂], miss
- 1: [0001₂], hit
- 7: [0111₂], miss
- 8: [1000₂], miss
- 0: [0000₂], miss

<table>
<thead>
<tr>
<th>v</th>
<th>Tag</th>
<th>Block</th>
</tr>
</thead>
<tbody>
<tr>
<td>Set 0</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>Set 1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Set 2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Set 3</td>
<td>1</td>
<td>0</td>
</tr>
</tbody>
</table>
E-way Set Associative Cache (Here: E = 2)

E = 2: Two lines per set
Assume: cache block size 8 bytes

Address of short int:

```
   | tag | 0 1 2 3 4 5 6 7 |
---|------|------------------|
100|      | 0...01           |
```

find set
E-way Set Associative Cache (Here: E = 2)

E = 2: Two lines per set
Assume: cache block size 8 bytes

Address of short int:

<table>
<thead>
<tr>
<th>t bits</th>
<th>0...01</th>
<th>100</th>
</tr>
</thead>
</table>

valid? +
match: yes = hit

compare both

block offset

v  tag  0 1 2 3 4 5 6 7  v  tag  0 1 2 3 4 5 6 7
E-way Set Associative Cache (Here: \(E = 2\))

\(E = 2\): Two lines per set
Assume: cache block size 8 bytes

No match:
- One line in set is selected for eviction and replacement
- Replacement policies: random, least recently used (LRU), ...
2-Way Set Associative Cache Simulation

M=16 byte addresses, B=2 bytes/block, S=2 sets, E=2 blocks/set

Address trace (reads, one byte per read):

<table>
<thead>
<tr>
<th>Address</th>
<th>Tag</th>
<th>Block</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>00</td>
<td>M[0-1]</td>
</tr>
<tr>
<td>1</td>
<td>10</td>
<td>M[8-9]</td>
</tr>
<tr>
<td>7</td>
<td>01</td>
<td>M[6-7]</td>
</tr>
<tr>
<td>8</td>
<td></td>
<td></td>
</tr>
<tr>
<td>0</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
What about writes?

- Multiple copies of data exist:
  - L1, L2, L3, Main Memory, Disk

- What to do on a write-hit?
  - Write-through (write immediately to memory)
  - Write-back (defer write to memory until replacement of line)
    - Need a dirty bit (line different from memory or not)

- What to do on a write-miss?
  - Write-allocate (load into cache, update line in cache)
    - Good if more writes to the location follow
  - No-write-allocate (writes straight to memory, does not load into cache)

- Typical
  - Write-through + No-write-allocate
  - Write-back + Write-allocate
Intel Core i7 Cache Hierarchy

Processor package

Core 0

- Regs
- L1 d-cache
- L1 i-cache
- L2 unified cache

Core 3

- Regs
- L1 d-cache
- L1 i-cache
- L2 unified cache

... (shared by all cores)

L1 i-cache and d-cache: 32 KB, 8-way, Access: 4 cycles

L2 unified cache: 256 KB, 8-way, Access: 10 cycles

L3 unified cache: 8 MB, 16-way, Access: 40-75 cycles

Block size: 64 bytes for all caches.

Main memory
Cache Performance Metrics

- **Miss Rate**
  - Fraction of memory references not found in cache (misses / accesses) = 1 – hit rate
  - Typical numbers (in percentages):
    - 3-10% for L1
    - can be quite small (e.g., < 1%) for L2, depending on size, etc.

- **Hit Time**
  - Time to deliver a line in the cache to the processor
    - includes time to determine whether the line is in the cache
  - Typical numbers:
    - 4 clock cycle for L1
    - 10 clock cycles for L2

- **Miss Penalty**
  - Additional time required because of a miss
    - typically 50-200 cycles for main memory (Trend: increasing!)
Let’s think about those numbers

- **Huge difference between a hit and a miss**
  - Could be 100x, if just L1 and main memory

- **Would you believe 99% hits is twice as good as 97%?**
  - Consider:
    - cache hit time of 1 cycle
    - miss penalty of 100 cycles
  - Average access time:
    - 97% hits: 1 cycle + 0.03 * 100 cycles = 4 cycles
    - 99% hits: 1 cycle + 0.01 * 100 cycles = 2 cycles

- **This is why “miss rate” is used instead of “hit rate”**
Writing Cache Friendly Code

- Make the common case go fast
  - Focus on the inner loops of the core functions

- Minimize the misses in the inner loops
  - Repeated references to variables are good (temporal locality)
  - Stride-1 reference patterns are good (spatial locality)

Key idea: Our qualitative notion of locality is quantified through our understanding of cache memories
Today

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- Performance impact of caches
  - The memory mountain
  - Rearranging loops to improve spatial locality
  - Using blocking to improve temporal locality
The Memory Mountain

- **Read throughput** (read bandwidth)
  - Number of bytes read from memory per second (MB/s)

- **Memory mountain**: Measured read throughput as a function of spatial and temporal locality.
  - Compact way to characterize memory system performance.
long data[MAXELEMS]; /* Global array to traverse */

/* test - Iterate over first "elems" elements of array “data” with stride of "stride", using 4x4 loop unrolling. */

int test(int elems, int stride) {
    long i, sx2=stride*2, sx3=stride*3, sx4=stride*4;
    long acc0 = 0, acc1 = 0, acc2 = 0, acc3 = 0;
    long length = elems, limit = length - sx4;

    /* Combine 4 elements at a time */
    for (i = 0; i < limit; i += sx4) {
        acc0 = acc0 + data[i];
        acc1 = acc1 + data[i+stride];
        acc2 = acc2 + data[i+sx2];
        acc3 = acc3 + data[i+sx3];
    }

    /* Finish any remaining elements */
    for (; i < length; i++) {
        acc0 = acc0 + data[i];
    }

    return ((acc0 + acc1) + (acc2 + acc3));
}

Call test() with many combinations of elems and stride.

For each elems and stride:

1. Call test() once to warm up the caches.

2. Call test() again and measure the read throughput (MB/s)
The Memory Mountain

- Core i7 Haswell
  - 2.1 GHz
  - 32 KB L1 d-cache
  - 256 KB L2 cache
  - 8 MB L3 cache
  - 64 B block size

- Aggressive prefetching
- Ridges of temporal locality
- Slopes of spatial locality

Read throughput (MB/s)

Stride (x8 bytes)

Size (bytes)
Today

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Matrix Multiplication Example

- **Description:**
  - Multiply N x N matrices
  - Matrix elements are doubles (8 bytes)
  - O(N^3) total operations
  - N reads per source element
  - N values summed per destination
    - but may be able to hold in register

```c
/* ijk */
for (i=0; i<n; i++) {
    for (j=0; j<n; j++) {
        sum = 0.0;
        for (k=0; k<n; k++)
            sum += a[i][k] * b[k][j];
        c[i][j] = sum;
    }
}
```

Variable sum held in register
Miss Rate Analysis for Matrix Multiply

**Assume:**
- Block size = 32B (big enough for four doubles)
- Matrix dimension (N) is very large
  - Approximate $1/N$ as 0.0
- Cache is not even big enough to hold multiple rows

**Analysis Method:**
- Look at access pattern of inner loop
Layout of C Arrays in Memory (review)

- **C arrays allocated in row-major order**
  - each row in contiguous memory locations

- **Stepping through columns in one row:**
  - `for (i = 0; i < N; i++)`
    - `sum += a[0][i];`
  - accesses successive elements
  - if block size (B) > `sizeof(a_{ij})` bytes, exploit spatial locality
    - miss rate = `sizeof(a_{ij}) / B`

- **Stepping through rows in one column:**
  - `for (i = 0; i < n; i++)`
    - `sum += a[i][0];`
  - accesses distant elements
  - no spatial locality!
    - miss rate = 1 (i.e. 100%)
Matrix Multiplication (ijk)

```c
/* ijk */
for (i=0; i<n; i++) {
    for (j=0; j<n; j++) {
        sum = 0.0;
        for (k=0; k<n; k++)
            sum += a[i][k] * b[k][j];
        c[i][j] = sum;
    }
}
```

Misses per inner loop iteration:

<table>
<thead>
<tr>
<th></th>
<th>A</th>
<th>B</th>
<th>C</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0.25</td>
<td>1.0</td>
<td>0.0</td>
</tr>
</tbody>
</table>
Matrix Multiplication (jik)

/* jik */
for (j=0; j<n; j++) {
    for (i=0; i<n; i++) {
        sum = 0.0;
        for (k=0; k<n; k++)
            sum += a[i][k] * b[k][j];
        c[i][j] = sum
    }
}

Inner loop:

Misses per inner loop iteration:

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</table>
Matrix Multiplication (kij)

/* kij */
for (k=0; k<n; k++) {
    for (i=0; i<n; i++) {
        r = a[i][k];
        for (j=0; j<n; j++)
            c[i][j] += r * b[k][j];
    }
}

Inner loop:
(i,k) (k,*) (i,*)

Misses per inner loop iteration:

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<th>A</th>
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<tbody>
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<td>0.0</td>
<td>0.25</td>
<td>0.25</td>
</tr>
</tbody>
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Matrix Multiplication (ikj)

```c
/* ikj */
for (i=0; i<n; i++) {
    for (k=0; k<n; k++) {
        r = a[i][k];
        for (j=0; j<n; j++)
            c[i][j] += r * b[k][j];
    }
}
```

Misses per inner loop iteration:

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<td>0.25</td>
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</table>

**Inner loop:**

- **Fixed**
- **Row-wise**

A  B  C

**matmult/mm.c**

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Matrix Multiplication (jki)

#include <stdio.h>

void matmult(int n, int a[100][100], int b[100][100], int c[100][100]) {
    int j, k, i;
    for (j = 0; j < n; j++) {
        for (k = 0; k < n; k++) {
            float r = b[k][j];
            for (i = 0; i < n; i++)
                c[i][j] += a[i][k] * r;
        }
    }
}

int main() {
    int n = 100;
    int A[100][100], B[100][100], C[100][100];
    // Initialize A, B, and C
    matmult(n, A, B, C);
    // Print C
    return 0;
}

Misses per inner loop iteration:

\[
\begin{array}{ccc}
A & B & C \\
1.0 & 0.0 & 1.0 \\
\end{array}
\]
Matrix Multiplication (kji)

```c
/* kji */
for (k=0; k<n; k++) {
    for (j=0; j<n; j++) {
        r = b[k][j];
        for (i=0; i<n; i++)
            c[i][j] += a[i][k] * r;
    }
}
```

Misses per inner loop iteration:

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</tr>
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<tbody>
<tr>
<td></td>
<td>1.0</td>
<td>0.0</td>
<td>1.0</td>
</tr>
</tbody>
</table>
Summary of Matrix Multiplication

for (i=0; i<n; i++) {
    for (j=0; j<n; j++) {
        sum = 0.0;
        for (k=0; k<n; k++)
            sum += a[i][k] * b[k][j];
        c[i][j] = sum;
    }
}

for (k=0; k<n; k++) {
    for (i=0; i<n; i++) {
        r = a[i][k];
        for (j=0; j<n; j++)
            c[i][j] += r * b[k][j];
    }
}

for (j=0; j<n; j++) {
    for (k=0; k<n; k++) {
        r = b[k][j];
        for (i=0; i<n; i++)
            c[i][j] += a[i][k] * r;
    }
}

ijk (\& jik):
- 2 loads, 0 stores
- misses/iter = 1.25

kij (\& ikj):
- 2 loads, 1 store
- misses/iter = 0.5

jki (\& kji):
- 2 loads, 1 store
- misses/iter = 2.0
Core i7 Matrix Multiply Performance

Cycles per inner loop iteration

Array size (n)

ijk / jik
jki / kji
kij / ikj
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Example: Matrix Multiplication

c = (double *) calloc(sizeof(double), n*n);

/* Multiply n x n matrices a and b */
void mmm(double *a, double *b, double *c, int n) {
    int i, j, k;
    for (i = 0; i < n; i++)
        for (j = 0; j < n; j++)
            for (k = 0; k < n; k++)
                c[i*n + j] += a[i*n + k] * b[k*n + j];
}
Cache Miss Analysis

- **Assume:**
  - Matrix elements are doubles
  - Cache block = 8 doubles
  - Cache size $C \ll n$ (much smaller than $n$)

- **First iteration:**
  - $n/8 + n = 9n/8$ misses
  - Afterwards in cache: (schematic)
Cache Miss Analysis

- **Assume:**
  - Matrix elements are doubles
  - Cache block = 8 doubles
  - Cache size $C \ll n$ (much smaller than $n$)

- **Second iteration:**
  - Again:
    - $n/8 + n = 9n/8$ misses

- **Total misses:**
  - $9n/8 \times n^2 = (9/8) \times n^3$
Blocked Matrix Multiplication

c = (double *) calloc(sizeof(double), n*n);

/* Multiply n x n matrices a and b */
void mmm(double *a, double *b, double *c, int n) {
    int i, j, k;
    for (i = 0; i < n; i+=B)
        for (j = 0; j < n; j+=B)
            for (k = 0; k < n; k+=B)
                /* B x B mini matrix multiplications */
                for (i1 = i; i1 < i+B; i++)
                    for (j1 = j; j1 < j+B; j++)
                        for (k1 = k; k1 < k+B; k++)
                            c[i1*n+j1] += a[i1*n + k1]*b[k1*n + j1];
}

Block size B x B

matmult/bmm.c
Cache Miss Analysis

Assume:
- Cache block = 8 doubles
- Cache size $C \ll n$ (much smaller than $n$)
- Three blocks fit into cache: $3B^2 < C$

First (block) iteration:
- $B^2/8$ misses for each block
- $2n/B * B^2/8 = nB/4$ (omitting matrix $c$)
- Afterwards in cache (schematic)
Cache Miss Analysis

- Assume:
  - Cache block = 8 doubles
  - Cache size $C << n$ (much smaller than $n$)
  - Three blocks fit into cache: $3B^2 < C$

- Second (block) iteration:
  - Same as first iteration
  - $2n/B * B^2/8 = nB/4$

- Total misses:
  - $nB/4 * (n/B)^2 = n^3/(4B)$
Blocking Summary

- No blocking: \((9/8) \times n^3\)
- Blocking: \(1/(4B) \times n^3\)

- Suggest largest possible block size \(B\), but limit \(3B^2 < C\)!

- Reason for dramatic difference:
  - Matrix multiplication has inherent temporal locality:
    - Input data: \(3n^2\), computation \(2n^3\)
    - Every array elements used \(O(n)\) times!
  - But program has to be written properly
Cache Summary

- Cache memories can have significant performance impact

- You can write your programs to exploit this!
  - Focus on the inner loops, where bulk of computations and memory accesses occur.
  - Try to maximize spatial locality by reading data objects with sequentially with stride 1.
  - Try to maximize temporal locality by using a data object as often as possible once it’s read from memory.
Per-lecture feedback

- Better sooner rather than later!
- I can help with issues sooner.
- There is a per-lecture feedback form.
- **The form is anonymous.**
  (It checks that you’re at Illinois Tech to filter abuse, but I don’t see who submitted any of the forms.)
- [https://forms.gle/qoeEbBuTYXo5FiU1A](https://forms.gle/qoeEbBuTYXo5FiU1A)
- I’ll remind about this at each lecture.