CS429: Computer Organization and Architecture
Optimization II

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Cache Performance Metrics

**Miss Rate**
- Fraction of memory references not found in cache (misses / references)
- Typical numbers: 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 (including time to determine whether the line is in the cache).
- Typical numbers: 1-3 clock cycles for L1; 5-12 clock cycles for L2.

**Miss Penalty**
- Additional time required because of a miss.
- Typically 100-300 cycles for main memory.
Repeated references to variables are good (temporal locality).

Stride-1 reference patterns are good (spatial locality).

Examples:
Assume cold cache, 4-byte words, 4 word (16-byte) cache blocks.

```c
int sumarrayrows(int a[M][N])
{
    int i, j, sum = 0;
    for (i = 0; i < M; i++)
        for (j = 0; j < N; j++)
            sum += a[i][j];
    return sum;
}
```

Miss rate = 1/4 = 25%

```c
int sumarraycols(int a[M][N])
{
    int i, j, sum = 0;
    for (j = 0; j < N; j++)
        for (i = 0; i < M; i++)
            sum += a[i][j];
    return sum;
}
```

Miss rate = 100%
Why would performance drop as the working set gets very small?
Ridges of Temporal Locality

Slice through the memory mountain with stride = 1. This illustrates read throughput with different caches and memory.

![Bar chart showing read throughput for different working set sizes and cache regions. The x-axis represents working set size in bytes (8m, 4m, 2m, 1024k, 512k, 256k, 128k, 64k, 32k, 16k, 8k, 4k, 2k, 1k). The y-axis represents read throughput in MB/s.](chart_image)
A Slope of Spatial Locality

Slice through memory mountain with size = 256KB. This shows cache block size.

![Graph showing read throughput (MB/s) vs stride (words)]
Anomaly in Memory Mountain

Why does the memory mountain drop off at the back? Prof. Warren Hunt told me: “When I looked into this issue, I didn’t come to a clean resolution. Perhaps the dropoff is a measurement anomaly; the times are so short in comparison to the measurement costs that it appears that the performance is degrading.”
Matrix Multiplication Example

Major Cache Effects to Consider.

- Total cache size: Exploit temporal locality and keep the working set small.
- Block size: Exploit spatial locality.

Description

- Multiply $N \times N$ matrices.
- $O(N^3)$ total operations.
- Accesses:
  - $N$ reads per source element.
  - $N$ values summed per destination (but may be held in register).

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

- Line size = 32B (big enough for 4 64-bit words)
- Matrix dimension $N$ is very large.
- We can approximate $1/N$ as 0.0.
- Cache is not even big enough to hold multiple rows.

**Analysis Method:** Look at access pattern of the inner loop.
C arrays are allocated in row-major order.
- Each row is allocated in contiguous memory locations.

Stepping through columns in one row:
```c
for (i = 0; i < N; i++)
    sum += a[j][i];
```
- This accesses successive elements.
- If block size $B > 4$ bytes, exploits spatial locality.
- Compulsory miss rate = $4$ bytes / $B$.

Stepping through rows in one column:
```c
for (i = 0; i < N; i++)
    sum += a[i][i];
```
- Accesses distant elements.
- No spatial locality!
- Compulsory 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;     // in reg
        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)

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

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<tbody>
<tr>
<td></td>
<td>0.25</td>
<td>1.0</td>
<td>0.0</td>
</tr>
</tbody>
</table>
/ * 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];
    }
}

Misses per Inner Loop Iteration:

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<tr>
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<th>C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Iteration</td>
<td>0.0</td>
<td>0.25</td>
<td>0.25</td>
</tr>
</tbody>
</table>
Matrix Multiplication (ikj)

```c
/* ijk */
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];
    }
}
```

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</tbody>
</table>
Matrix Multiplication (jki)

```c
/* jki */
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;
    }
}
```

Misses per Inner Loop Iteration:

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

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

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

**jki (& kji):**
- 2 loads, 1 store
- misses / iteration = 2.0

*Miss rates are important, but not perfect predictors of performance.* Code scheduling matters, also.
The programmer can optimize for cache performance.
- How data structures are organized.
- How data are accessed (e.g., nested loop structure).

All systems favor “cache friendly code.”
- Getting absolute optimum performance is very platform specific.
- Involves cache sizes, line sizes, associativities, etc.
- Can get most advantage with generic code.
- Keep working set reasonably small (temporal locality).
- Use small strides (spatial locality).