CS429: Computer Organization and Architecture
Cache I

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Locality

**Principle of Locality:**

- Programs tend to reuse data and instructions near those used recently, or that were recently referenced.
- **Temporal locality:** Recently referenced items are likely to be referenced in the near future.
- **Spatial locality:** Items with nearby addresses tend to be referenced close together in time.

```plaintext
sum = 0;
for (i = 0; i < n; i++)
    sum += a[i];
return sum;
```

**Data:**
- Reference array elements in succession (stride-1): Spatial
- Reference sum each iteration: Temporal

**Instructions:**
- Reference instructions in sequence: Spatial
- Cycle through loop repeatedly: Temporal
Claim: Being able to look at code and get a qualitative sense of its locality is a key skill for a professional programmer.

Question: Does this function have good locality?

```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;
}
```
**Question:** Does *this* function have good locality? How does it compare to the previous version?

```c
int sumarrayrows( 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;
}
```
Question: Can you permute the loops so that this function scans
the 3-d array a with a stride-1 reference pattern (and thus has
good spatial locality)?

```c
int sumarray3d( int a[M][N][N] )
{
    int i, j, k, sum = 0;

    for ( i = 0; i < M; i++ )
        for ( j = 0; j < N; j++ )
            for ( k = 0; k < N; k++ )
                sum += a[k][i][j];

    return sum;
}
```
Some fundamental and enduring properties of hardware and software:

- Fast storage technologies cost more per byte and have less capacity.
- The gap between CPU and main memory speed is widening.
- Well-written programs tend to exhibit good locality.

These fundamental properties complement each other beautifully.

They suggest an approach for organizing memory and storage systems known as a *memory hierarchy*.
Example Memory Hierarchy

- **Registers**
  - CPU registers hold words retrieved from L1 cache
- **L1 cache (SRAM)**
  - L1 cache holds cache lines retrieved from L2 cache
- **L2 cache (SRAM)**
  - L2 cache holds cache lines retrieved from main memory
- **Main memory (DRAM)**
  - Main memory holds disk blocks retrieved from local disks
- **Local secondary storage (local disks)**
  - Local disks hold files retrieved from disks on remote network servers
- **Remote secondary storage (tapes, distributed file systems, Web servers)**

- Smaller, faster, costlier per byte
- Larger, slower, cheaper per byte
**Cache**: A smaller, faster storage device that acts as a staging area for a subset of the data in a larger, slower device.

The fundamental idea of a memory hierarchy: For each $k$, the faster, smaller device at level $k$ serves as a cache for the larger, slower device at level $k+1$. 
Why do memory hierarchies work?

- Programs tend to access the data at level $k$ more often than they access the data at level $k+1$.
- Thus, the storage at level $k+1$ can be slower, and thus larger and cheaper per bit.
- *Net effect:* A large pool of memory that costs as much as the cheap storage near the bottom, but that serves data to programs at the rate of the fast storage near the top.
- We use a combination of small fast memory and big slow memory to give the illusion of big fast memory.
Smaller, faster, more expensive device at level k caches a subset of the blocks from level k+1.

Data is copied between levels in block-sized transfer units.

Larger, slower, cheaper storage device at level k+1 is partitioned into blocks.
Program needs object d, stored in some block b.

**Cache hit:** program finds b in the level k cache, e.g., block 14.

**Cache miss:** b is not at level k, so must fetch it from level k+1, e.g., block 12.

- If level k cache is full, then some current block must be replaced (evicted). Which one is the “victim”?

**Placement policy:** where can the new block go? E.g., b mod 4.

**Replacement policy:** Which block should be evicted? E.g., LRU.
Types of cache misses:

*Cold (compulsory) miss*: the cache is empty.

*Conflict miss*: all available positions at level k are occupied.
- Most caches limit blocks at level k+1 to a small subset (sometimes only one) of the block positions at level k.
- E.g., Block i at level k+1 must be placed in block (i mod 4) at level k+1.
- Conflict misses occur when multiple data objects all map to the same level k block. Note: there still may be empty slots in the cache.
- E.g., Referencing blocks 0, 8, 0, 8, 0, 8, ... would miss every time.

*Capacity miss*: the set of active cache blocks (working set) is larger than the cache.
### Examples of Caching in the Hierarchy

<table>
<thead>
<tr>
<th>Cache type</th>
<th>What</th>
<th>Where</th>
<th>Latency (cycles)</th>
<th>Managed by</th>
</tr>
</thead>
<tbody>
<tr>
<td>Registers</td>
<td>4-byte word</td>
<td>CPU registers</td>
<td>0</td>
<td>compiler</td>
</tr>
<tr>
<td>TLB</td>
<td>address translations</td>
<td>On-chip TLB</td>
<td>0</td>
<td>hardware</td>
</tr>
<tr>
<td>L1 cache</td>
<td>32-byte block</td>
<td>On-chip L1</td>
<td>1</td>
<td>hardware</td>
</tr>
<tr>
<td>L2 cache</td>
<td>32-byte block</td>
<td>On-chip L2</td>
<td>10</td>
<td>hardware</td>
</tr>
<tr>
<td>Virtual Memory</td>
<td>4KB page</td>
<td>main memory</td>
<td>100</td>
<td>hw + OS</td>
</tr>
<tr>
<td>Buffer cache</td>
<td>parts of files</td>
<td>main memory</td>
<td>100</td>
<td>OS</td>
</tr>
<tr>
<td>Network buffer</td>
<td>parts of files</td>
<td>local disk</td>
<td>10M</td>
<td>AFS/NSF client</td>
</tr>
<tr>
<td>Network buffer cache</td>
<td>parts of files</td>
<td>local disk</td>
<td>10M</td>
<td>web browser</td>
</tr>
<tr>
<td>Browser cache</td>
<td>web pages</td>
<td>local disk</td>
<td>100</td>
<td>web proxy server</td>
</tr>
<tr>
<td>Web cache</td>
<td>web pages</td>
<td>remote server</td>
<td>1000M</td>
<td></td>
</tr>
</tbody>
</table>
Cache memories are small, fast SRAM-based memories managed automatically in hardware. They hold frequently accessed blocks of main memory.

CPU looks first for data in L1, then in L2, then in main memory.

The typical bus structure is shown below.
The tiny, very fast CPU register file has room for a small number of 4-byte words.

The transfer unit between register file and cache is a 4-byte block.

The small, fast L1 cache has room for \(k\) lines (each containing several words).

The transfer unit between cache and main memory is a block of bytes.

The big, slow main memory has room for many blocks.
Options: separate *data* and *instruction caches*, or a *unified cache*.

<table>
<thead>
<tr>
<th></th>
<th>registers</th>
<th>L1</th>
<th>L2</th>
<th>memory</th>
<th>disk</th>
</tr>
</thead>
<tbody>
<tr>
<td>size</td>
<td>200B</td>
<td>8-64KB</td>
<td>1-4MB SRAM</td>
<td>128MB DRAM</td>
<td>30GB</td>
</tr>
<tr>
<td>speed</td>
<td>3ns</td>
<td>3ns</td>
<td>6ns</td>
<td>60ns</td>
<td>8ms</td>
</tr>
<tr>
<td>$/MB</td>
<td>$100</td>
<td>$1.50</td>
<td>$0.05</td>
<td></td>
<td></td>
</tr>
<tr>
<td>line size</td>
<td>8B</td>
<td>32B</td>
<td>8KB</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Summary

This slideset:

- Locality: Spatial and Temporal
- Cache principles
- Multi-level cache hierarchies

Next time:

- Cache organization
- Replacement and writes
- Programming considerations