Memory Hierarchy and Caching

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Based on material by Randal E. Bryant and David R. O'Hallaron.

Locality of reference

Memory hierarchies

Cache organisation and operation

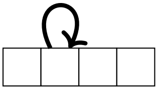
Cache performance

Locality

Principle of locality

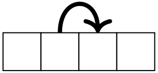
Programs tend to access data located near that which was accessed recently.

Temporal locality



Accessing data that was accessed recently.

Spatial locality



Accessing data that is close to data that was accessed recently.

- **General principles** — definition of “close” depends on the exact form of storage.
  - E.g. addresses for memory.

Locality example

```
double sum = 0;
for (int i = 0; i < n; i++) {
  sum += a[i];
}
```

Data references

- References array elements in succession (*stride* of 1).

Locality example

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Data references

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- References variable `sum` each iteration.

Locality example

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Data references

- References array elements in succession (*stride* of 1). **Spatial locality.**
- References variable `sum` each iteration. **Temporal locality.**

Instruction references

- Executes instructions in sequence.

Locality example

```c
double sum = 0;
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Data references

- References array elements in succession (*stride* of 1). **Spatial locality.**
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Instruction references

- Executes instructions in sequence. **Spatial locality.**
- Cycles through loop repeatedly.

Locality example

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Instruction references

- Executes instructions in sequence. **Spatial locality.**
- Cycles through loop repeatedly. **Temporal locality.**

Code as it's normally written has good locality by default, so we tend to focus only on *data locality*.

C array layout

```
int A[M][N];
```

To represent multi-dimensional arrays, C uses *row major order*.

Main consequence

- Rows are contiguous in memory.

Example

$$\begin{pmatrix} 11 & 12 & 13 & 14 \\ 21 & 22 & 23 & 24 \\ 31 & 32 & 33 & 34 \end{pmatrix}$$

is represented as

11	12	13	14	21	22	23	24	31	32	33	34

Implications

- `A[i][j]` and `A[i][j+1]` are adjacent.
- `A[i][j]` and `A[i+1][j]` are distant.

Eyeballing locality

Being able to glance at code and get a qualitative sense of its locality properties is a key skill for a programmer.

Does this function have good locality with respect to array `A`?

```
int sumrows(int A[M][N]) {
    int sum = 0;

    for (int i = 0; i < M; i++)
        for (int j = 0; j < N; j++)
            sum += A[i][j];
    return sum;
}
```

Does this function have good locality with respect to array `A`?

```
int sumcols(int A[M][N]) {
    int sum = 0;

    for (int j = 0; j < N; j++)
        for (int i = 0; i < M; i++)
            sum += A[i][j];
    return sum;
}
```

Transforming code for better locality

Can we permute the loops of this function such that we are accessing the memory of array `A` with a stride of 1?

```
int sum3d(int A[L][M][N]) {
    int sum = 0;

    for (int i = 0; i < M; i++)
        for (int j = 0; j < N; j++)
            for (int k = 0; k < L; k++)
                sum += A[k][i][j];
    return sum;
}
```

Transforming code for better locality

Can we permute the loops of this function such that we are accessing the memory of array `A` with a stride of 1?

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int sum3d(int A[L][M][N]) {
    int sum = 0;

    for (int i = 0; i < M; i++)
        for (int j = 0; j < N; j++)
            for (int k = 0; k < L; k++)
                sum += A[k][i][j];
    return sum;
}
```

Yes: place them in order `k`, `i`, `j`.

Locality of reference

Memory hierarchies

Cache organisation and operation

Cache performance

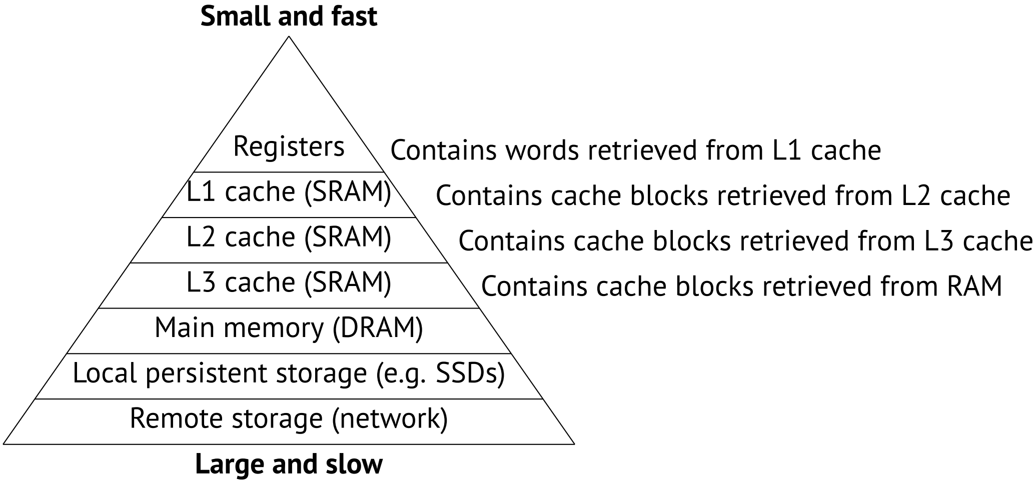
Memory hierarchies

Some fundamental and enduring properties of hardware and software

- Fast storage is expensive, has smaller capacity, and requires more power.
- There is a large gap between computational speed and memory speed.
- Well-written programs tend to exhibit good locality.

These properties suggest an approach for organising memory and other storage systems known as a *memory hierarchy*.

Example memory hierarchy



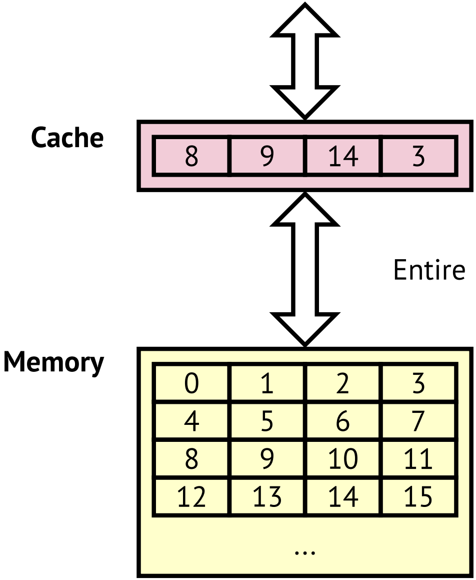
Caches

Definition of *cache*

A smaller, faster storage device that acts as a staging area for a subset of the data in a larger, slower device.

- **Fundamental idea of the memory hierarchy**
  - The smaller and faster device at level k acts as a cache for the larger slower device at level $k+1$.
- **Why do they work?**
  - Because of *locality*, most accesses tend to be towards the top of the hierarchy.
- **The ideal**
  - A huge pool of storage that is as cheap as at the bottom of the hiearchy, but as fast as at the top of the hierarchy.

Cache overview

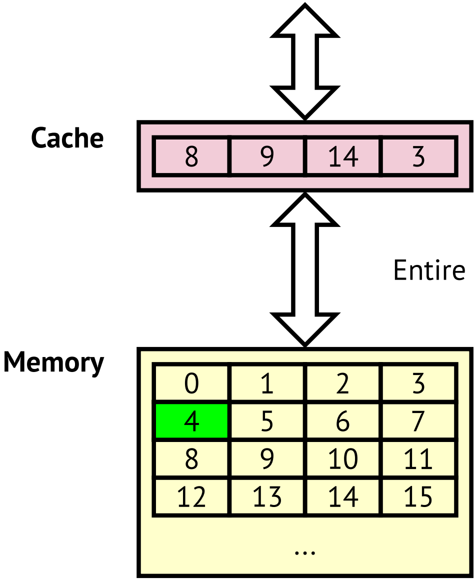


Small, fast, located on CPU, contains a subset of all blocks.

Entire blocks transmitted at once.

Large, remote, and slow, partitioned into uniform blocks of typically 16-256 bytes.

Cache overview



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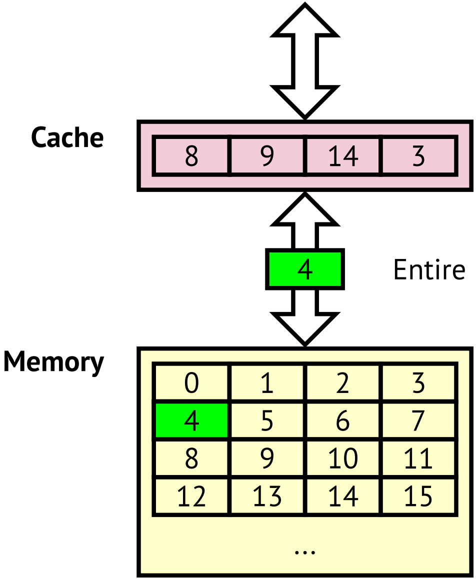

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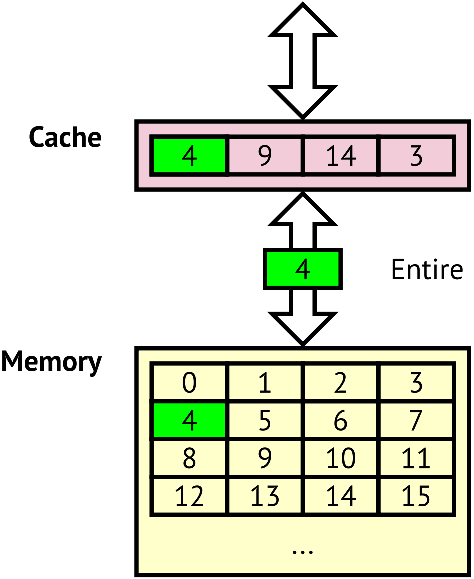

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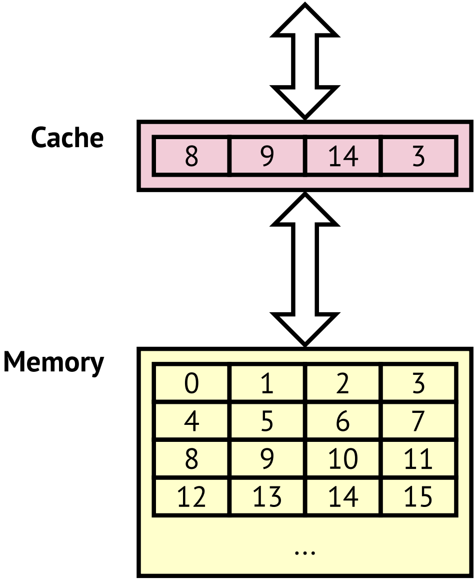
Example: cache hit



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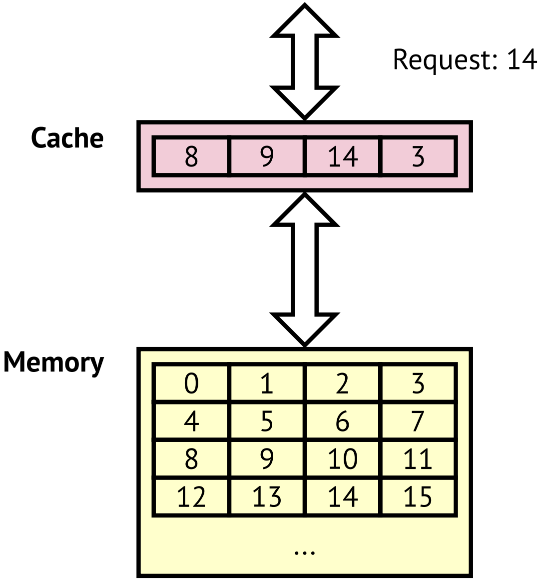
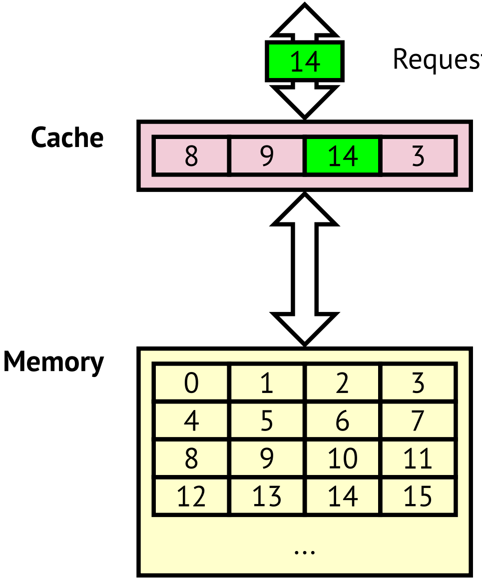


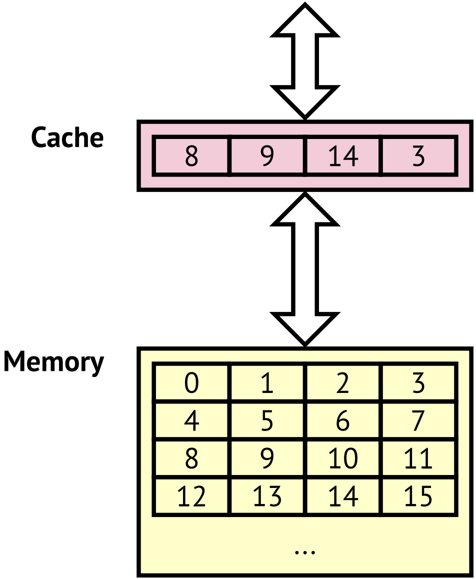
Example: cache hit



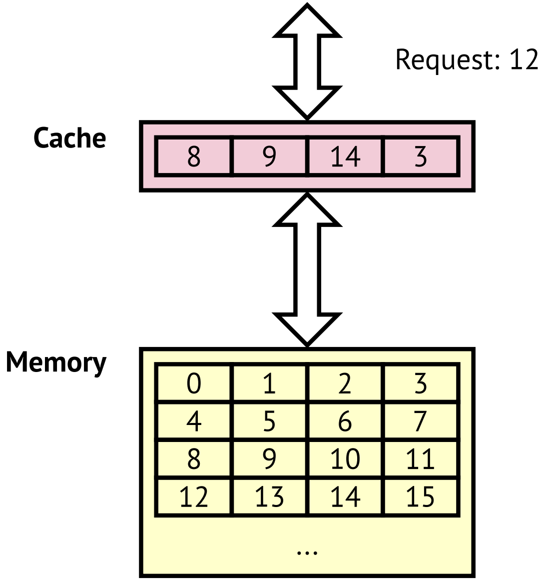
Request: 14

Block 14 is in cache: **Hit!**

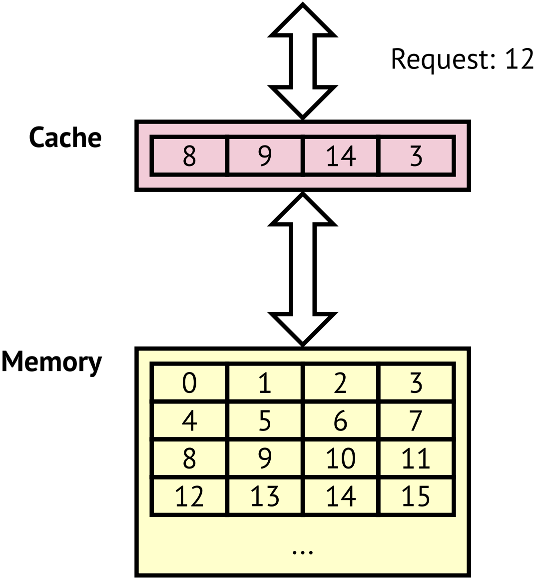
Example: cache miss



Example: cache miss

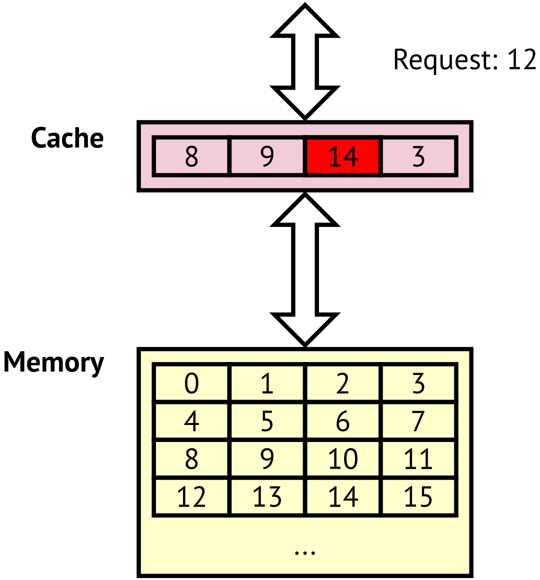


Example: cache miss



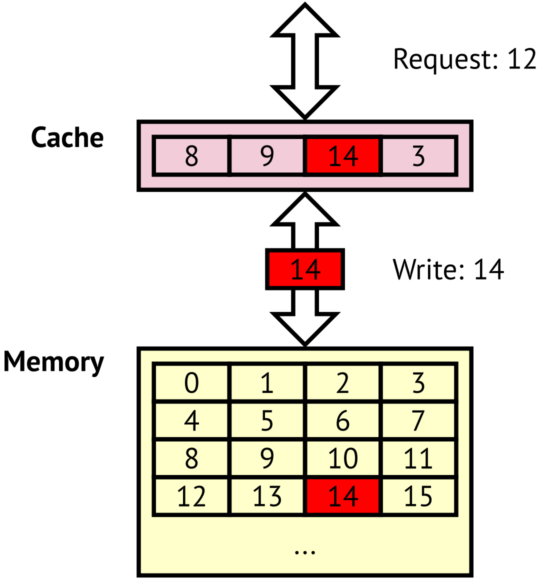
Block 12 is not in cache: **Miss!**

Example: cache miss



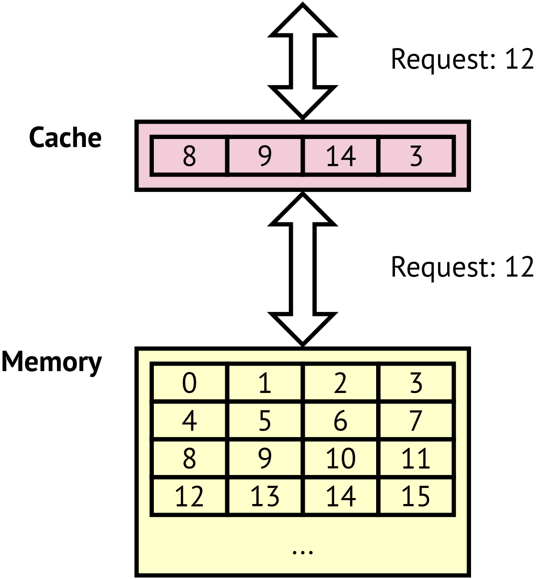
Select victim block for eviction.

Example: cache miss



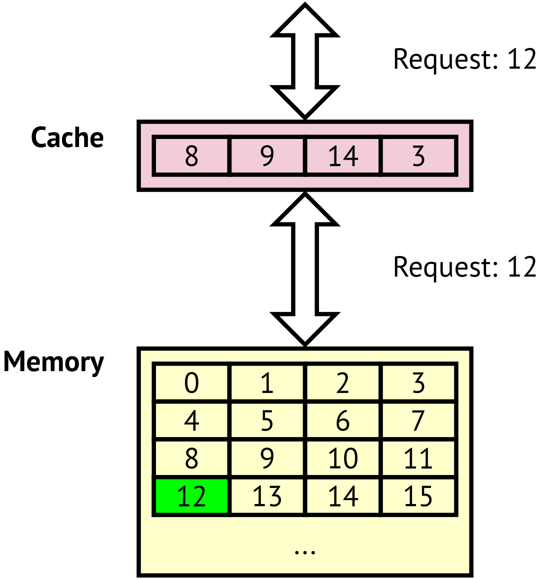
Save victim block in memory.

Example: cache miss



Retrieve new block from memory.

Example: cache miss



Retrieve new block from memory.

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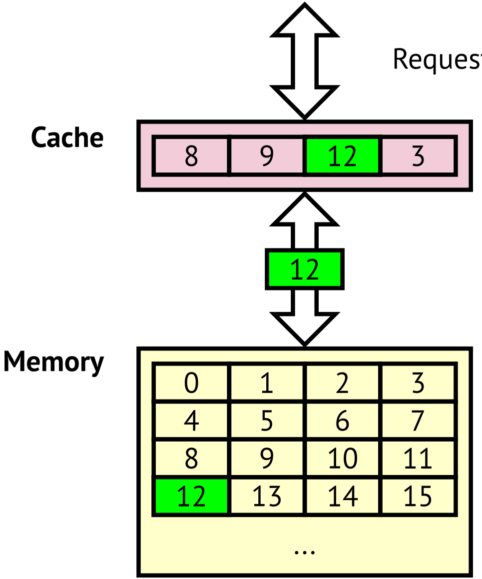
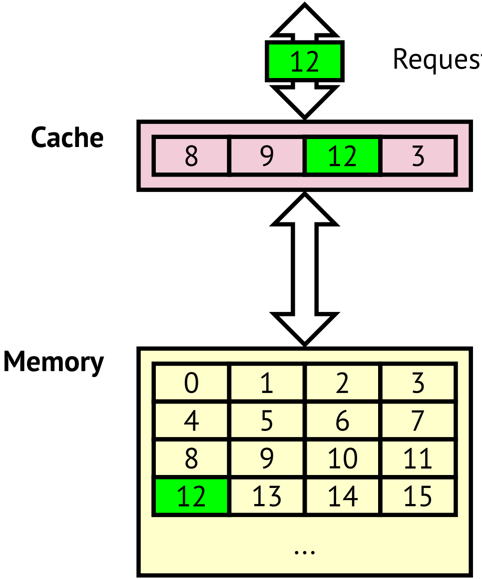


Request: 12

Put block in cache.

Example: cache miss



Request: 12

Respond to original request.

Types of cache misses

Cold/compulsory miss

- Occur when the cache is empty.
- Unavoidable when a program first starts.

Conflict miss

- Most caches limit blocks at level $k+1$ to a small subset of the slots at level k.
  - **Example:** Block i can only be located in slot $i \mod 4$.
- Causes conflicts when cache is large enough, but the blocks being accessed all map to the same slot.

Capacity miss

- Occurs when program *working set* exceeds size of cache.

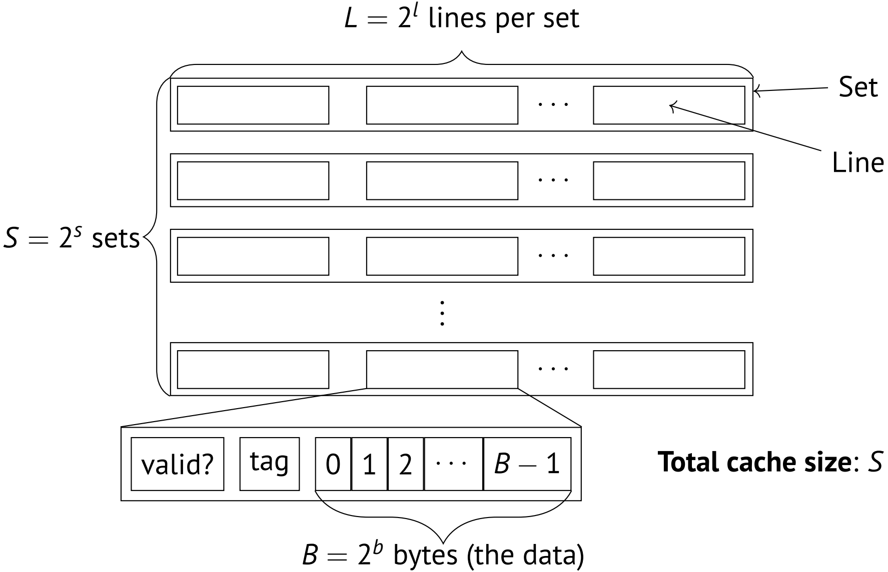
Locality of reference

Memory hierarchies

Cache organisation and operation

Cache performance

General structure of a cache for S, L, and B



Total cache size: $S \times L \times B$ bytes

Address structure

When $S = 2^n, B = 2^m$ we can easily split a w-bit address into *fields*, writing x_i for bit i.

$$\underbrace{x_{w-1} \cdots x_{b+s+1}}_{\text{tag}} \underbrace{x_{b+s} \cdots x_b}_{\text{set index}} \underbrace{x_{b-1} \cdots x_0}_{\text{block offset}}$$

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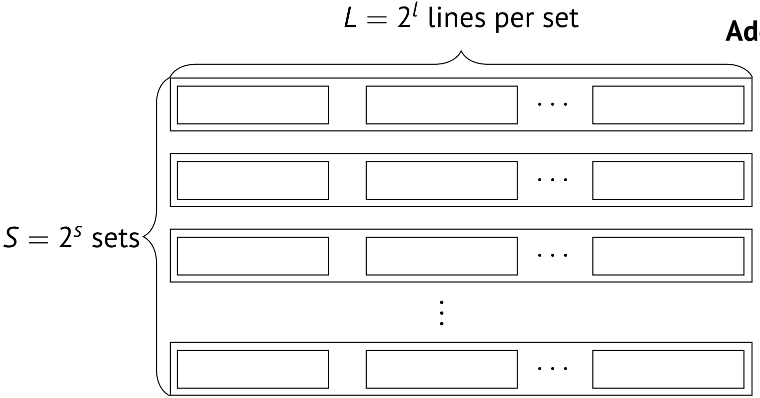
Example

Consider an 8-bit address with $m = 2, s = 3$.

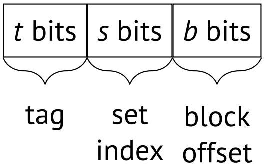
$$\underbrace{x_7 x_6 x_5}_{\text{tag}} \underbrace{x_4 x_3 x_2}_{\text{set index}} \underbrace{x_1 x_0}_{\text{offset}}$$

We look up an address in the cache by splitting the address into fields and looking up and checking based on their values.

Cache lookup



Address components:



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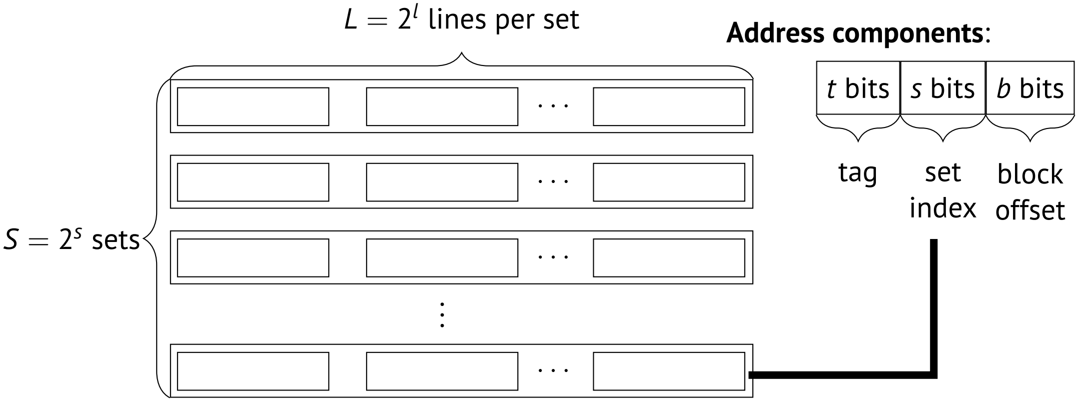

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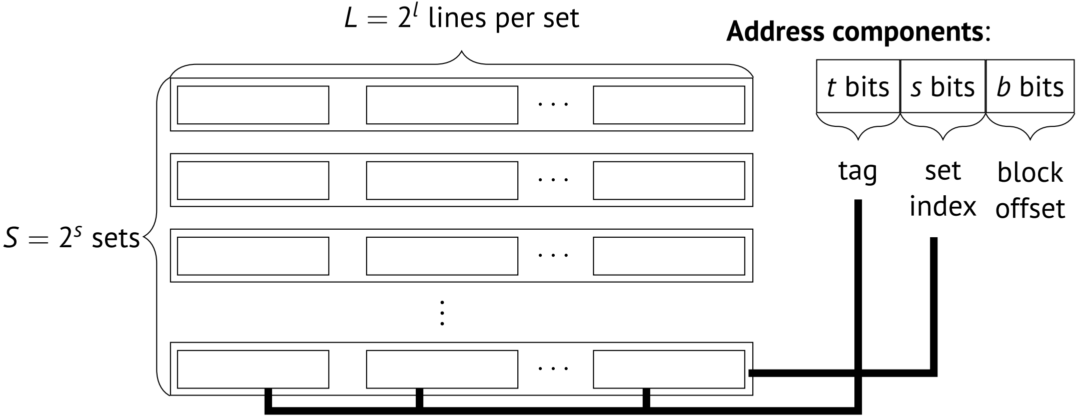

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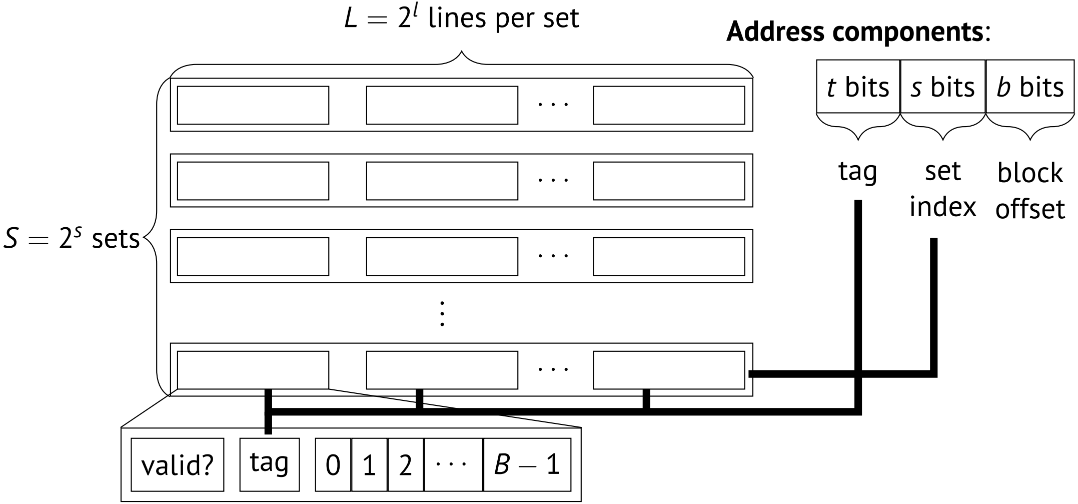

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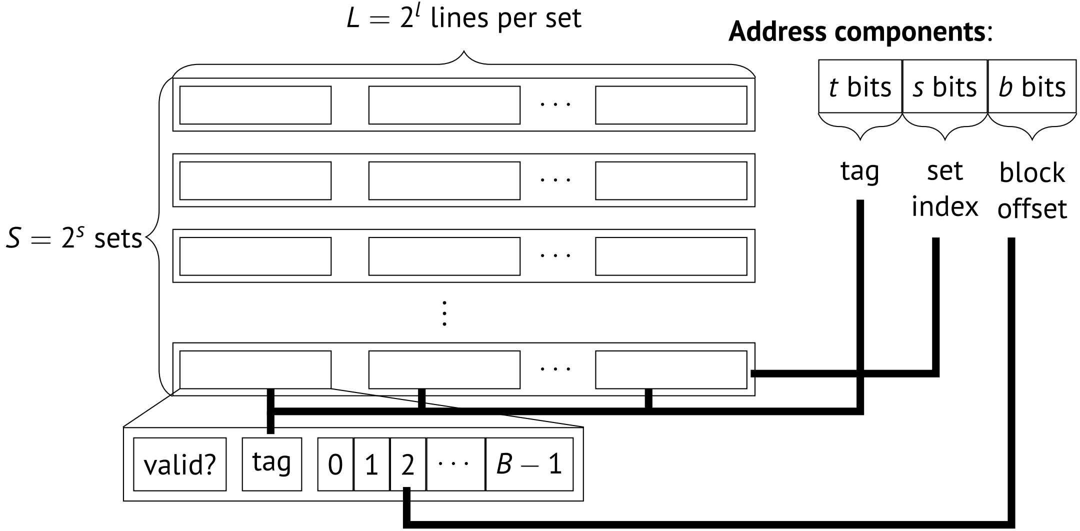

Example: Direct-Mapped ($L = 1$), with 4 sets and 8-byte blocks ($B = 8$)

Suppose 10-bit addresses, so $b = 3, s = 2, t = 6$. **Note:** one line per set.

v	tag	0	1	2	3	4	5	6	7
v	tag	0	1	2	3	4	5	6	7
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Address of 4-byte word

101010	10	100

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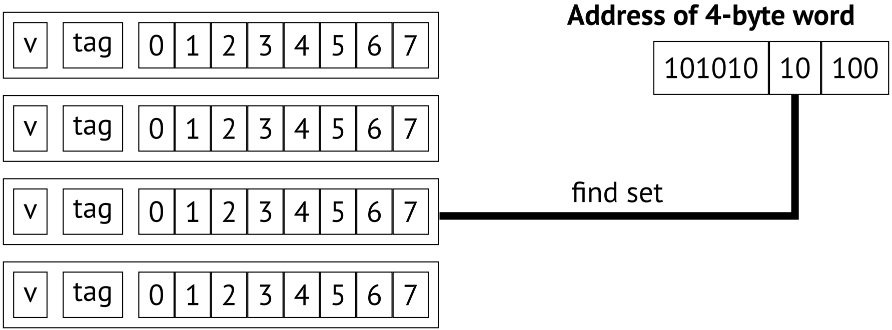

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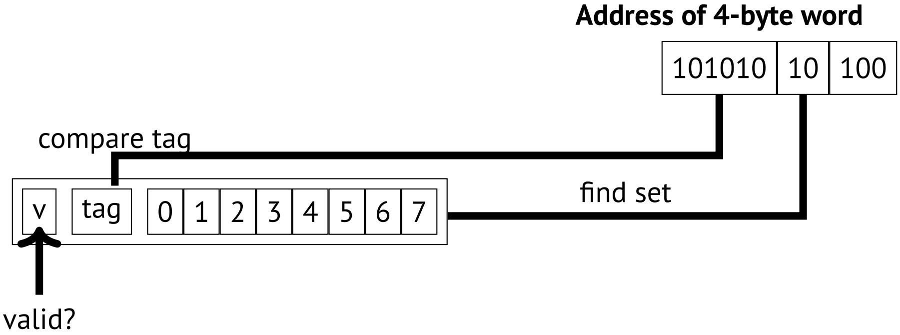

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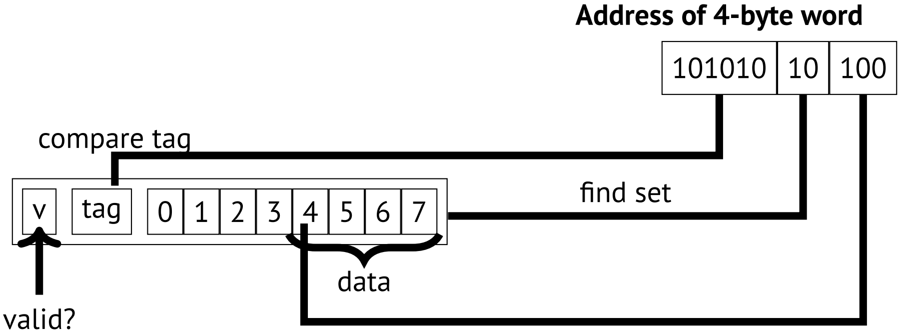

Simulation of Direct-Mapped Cache

Characteristics

10-bit addresses, $B = 8$, $S = 4$, $L = 1$.

$$\underbrace{x_9 x_8 x_7 x_6 x_5}_{\text{tag}}\,\underbrace{x_4 x_3}_{\text{set}}\,\underbrace{x_2 x_1 x_0}_{\text{offset}}$$

Simulation, reading single bytes from address

	Valid	Tag	Block
Set 0	0		
Set 1	0		
Set 2	0		
Set 3	0		

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Simulation, reading single bytes from address

- `00000 00 000`

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Simulation, reading single bytes from address

- `00000 00 000` **Miss**

	Valid	Tag	Block
Set 0	1	00000	Mem[0-7]
Set 1	0		
Set 2	0		
Set 3	0		

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- `00000 00 000` **Miss**
- `00000 00 001`

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Set 3	0		

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Simulation, reading single bytes from address

- `00000 00 000` **Miss**
- `00000 00 001` **Hit**

	Valid	Tag	Block
Set 0	1	00000	Mem[0-7]
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Set 2	0		
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- `00000 00 001` **Hit**
- `01000 11 100`

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Set 0	1	00000	Mem[0-7]
Set 1	0		
Set 2	0		
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Simulation, reading single bytes from address

- `00000 00 000` **Miss**
- `00000 00 001` **Hit**
- `01000 11 100` **Miss**
- `00001 00 000`

	Valid	Tag	Block
Set 0	1	00000	Mem[0-7]
Set 1	0		
Set 2	0		
Set 3	1	01000	Mem[280-287]

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Simulation, reading single bytes from address

- `00000 00 000` **Miss**
- `00000 00 001` **Hit**
- `01000 11 100` **Miss**
- `00001 00 000` **Miss**

	Valid	Tag	Block
Set 0	1	00001	Mem[32-39]
Set 1	0		
Set 2	0		
Set 3	1	01000	Mem[280-287]

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- `00000 00 001` **Hit**
- `01000 11 100` **Miss**
- `00001 00 000` **Miss**
- `00000 00 000` **Miss**

	Valid	Tag	Block
Set 0	1	00000	Mem[0-7]
Set 1	0		
Set 2	0		
Set 3	1	01000	Mem[280-287]

Example: Set-associative ($L = 2$), with 4 sets and 8-byte blocks ($B = 8$)

v	tag	0	1	2	3	4	5	6	7	v	tag	0	1	2	3	4	5	6	7
v	tag	0	1	2	3	4	5	6	7	v	tag	0	1	2	3	4	5	6	7
v	tag	0	1	2	3	4	5	6	7	v	tag	0	1	2	3	4	5	6	7
v	tag	0	1	2	3	4	5	6	7	v	tag	0	1	2	3	4	5	6	7

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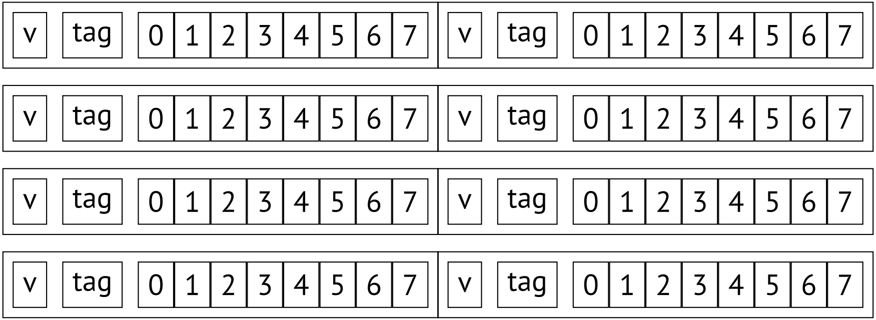
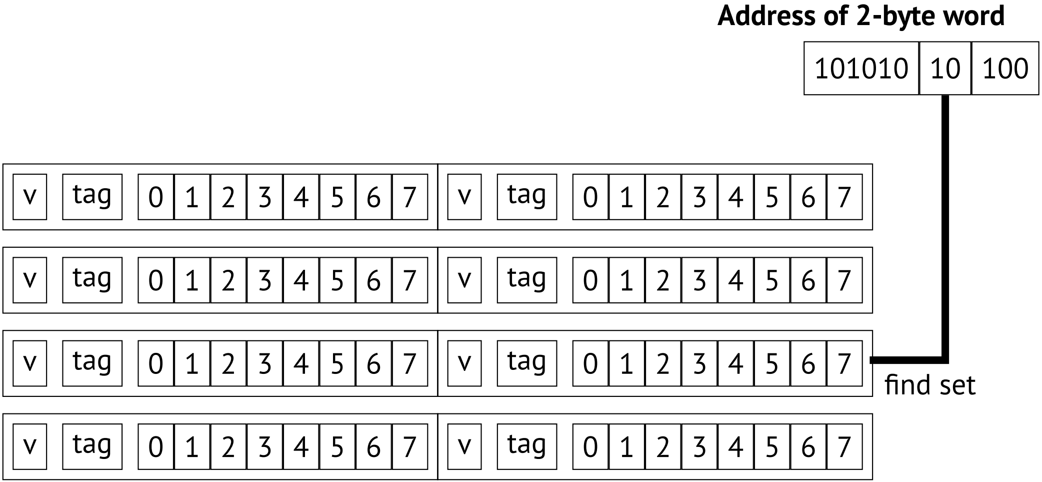
Address of 2-byte word

101010	10	100



Example: Set-associative ($L = 2$), with 4 sets and 8-byte blocks ($B = 8$)



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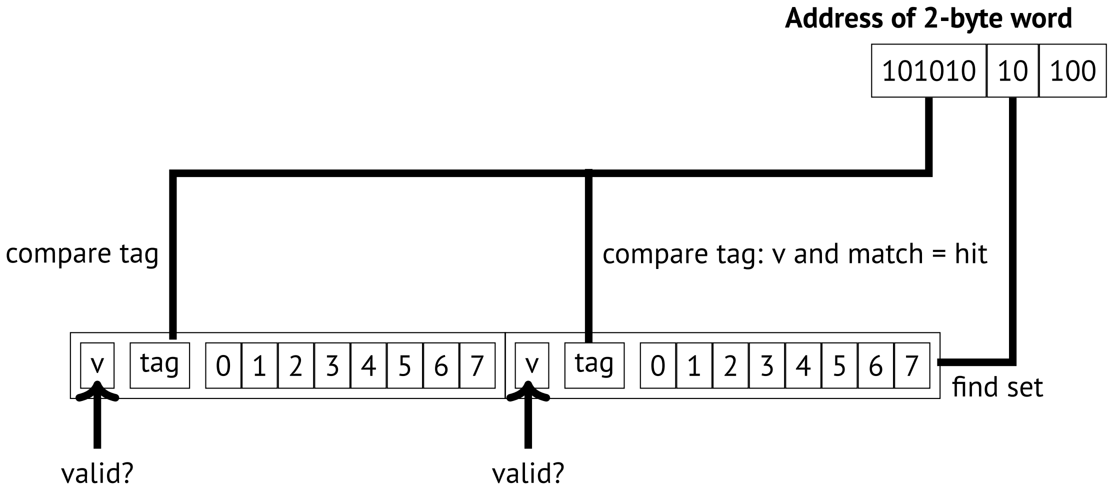

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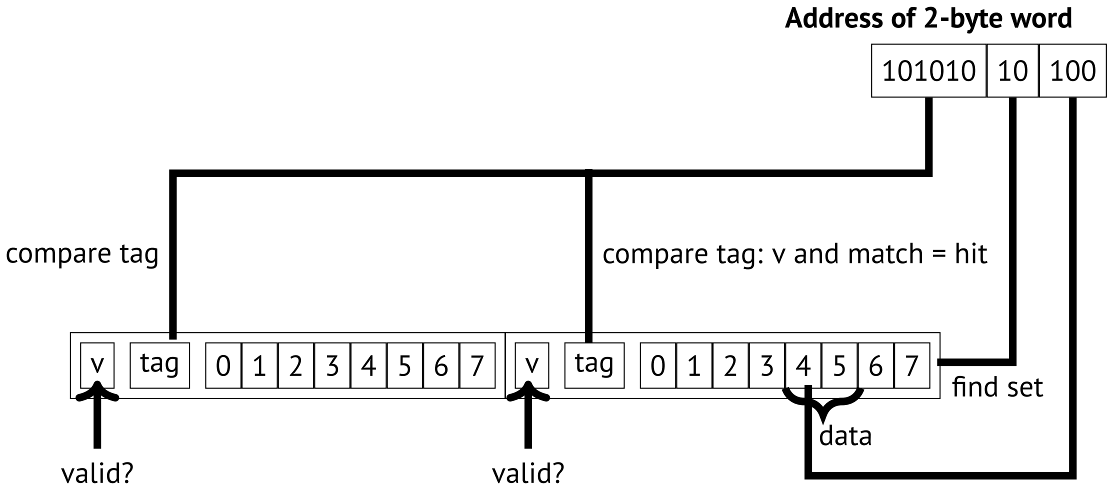

Simulation of 2-way set-associative cache

Characteristics

10-bit addresses, $B = 8$, $S = 1$, $L = 2$.

$$\underbrace{x_9 x_8 x_7 x_6 x_5 x_4}_{\text{tag}} \; \underbrace{x_3}_{\text{set}} \; \underbrace{x_2 x_1 x_0}_{\text{offset}}$$

Simulation, reading single bytes from address

	Valid	Tag	Block
Set 0	0		
	0		
Set 1	0		
	0		

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Simulation, reading single bytes from address

- 000000 0 000

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	0		
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Simulation, reading single bytes from address

- `000000 0 000` **Miss**

	Valid	Tag	Block
Set 0	1	000000	Mem[0-7]
	0		
Set 1	0		
	0		

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Simulation, reading single bytes from address

- `000000 0 000` **Miss**
- `000000 0 001`

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- `010001 1 100`

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	0		

What about writes?

Multiple copies of data exist

- L1, L2, L3 caches, main memory, disk, backup in the cloud…

What do we do on a write hit?

Write-through: writing immediately to the next level of the hierarchy.

Write-back: defer write until the cache block is evicted.

- Needs a *dirty bit* indicating whether block changed since it was loaded.

What do we do on a write miss?

Write-allocate: load block into cache and update there.

- Good if more writes follow.

No-write-allocate: write straight to next level, do not load into cache.

CPU caches are typically write-back and write-allocate.

Locality of reference

Memory hierarchies

Cache organisation and operation

Cache performance

A real cache

- Use `sudo dmidecode -t cache` or `lscpu` on Linux to see hardware details, including CPU cache specs.
- On an Ryzen 1700X, cache blocks are 64 bytes each, and
  - **L1:** 96KiB, 8-way set-associative, split into 32KiB for data (L1d) and 64KiB for instructions (L1i).
  - **L2:** 512KiB, 8-way set-associative.
  - **L3:** 16MiB, 8-way set associative.
- **But:** Each of the 8 cores have their own L1 and L2 caches, but L3 cache is shared.
  - For those who think caches are very fascinating, read up on *cache coherency protocols* and *false sharing*.

Cache performance metrics

Miss rate

- Fraction of memory references not found in cache ($misses \div accesses$).
- Typical numbers:
  - 3-10% for L1
  - Can be very small ($< 1\%$) for L2.

Hit time

- Time to deliver a cache block to the processor.
  - Includes time to determine whether a hit (checking tag).
- Typical numbers
  - L1: 4 clock cycles.
  - L2: 10 clock cycles.
  - L3: 40-75 cycles (depends on sharing).

Miss penalty

- Additional time needed because of a miss.
- Often over 100 cycles for main DRAM memory, historically increasing.

Conceptualising those numbers

- **Huge difference between a hit and a miss!**
  - Could be $100\times$ between L1 and main memory.
- 99% **hit rate may be twice as good as** 97%

  Cache hit time: 1 cycle

  Miss penalty: 100 cycles

  Average access time:
  - 97% hits: 1 cycle $+\ 0.03 \times 100$ cycles $=$ 4 cycles
  - 99% hits: 1 cycle $+\ 0.01 \times 100$ cycles $=$ 2 cycles
- **This is why we use *miss rate* instead of *hit rate*.**

Writing cache friendly code

- **Make the common case go fast.**
  - Focus on inner loops.
  - Optimising non-loopy code is almost never worth it.

Writing cache friendly code

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- **Ensure good locality.**
  - Avoid chasing ad-hoc pointers.
  - If you `malloc()` a million tiny blocks of memory, there is no guarantee they will be anywhere near each other.
    - Linked lists are *terrible*.

Writing cache friendly code

- **Make the common case go fast.**
  - Focus on inner loops.
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- **Ensure good locality.**
  - Avoid chasing ad-hoc pointers.
  - If you `malloc()` a million tiny blocks of memory, there is no guarantee they will be anywhere near each other.
    - Linked lists are *terrible*.
- **Minimise *footprint*.**
  - E.g. if all the data you work on fits in L3 cache, then you will never see an L3 cache miss after the initial ones.

Example: matrix multiplication

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

- Multiply *n*-by-*n* matrices in row-major order.
- Each element is a `double`
- $O(n^3)$ total opreations.
- *n* values summed per destination.

Miss rate analysis

Assume

- Cache block size $B = 64 bytes$
  - Enough for 8 `double`s.
- n is very large—approximate $1/n$ as 0.
- Cache is not even big enough to hold a single row or column.

Method

- Look at access pattern of inner loop.

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When accessing successive elements miss rate is $\texttt{sizeof}(\texttt{double})/B = 0.125$.

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for (int k=0; k<n; k++)
  sum += a[0][k]
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- Look at access pattern of inner loop.

When accessing successive elements miss rate is $\texttt{sizeof}(\texttt{double})/B = 0.125$.

```
for (int k=0; k<n; k++)
  sum += a[0][k]
```

When accessing distant elements miss rate is 1.

```
for (int k=0; k<n; k++)
  sum += a[k][0]
```

Matrix multiplication (ijk)

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

Misses per innermost loop iteration

a	b	c

Matrix multiplication (ijk)

```
for (int i=0; i<n; i++) {
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  }
}
```

Misses per innermost loop iteration

a	b	c
0.125	1	0

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Misses per innermost loop iteration

a	b	c
1	0	1

Matrix multiplication (kji)

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```

Misses per innermost loop iteration

a	b	c
1	0	1

Summary of variants

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

ijk and jik (inner loop):

- 2 loads, 0 stores
- 1.125 misses/iter

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

kij and ikj (inner loop):

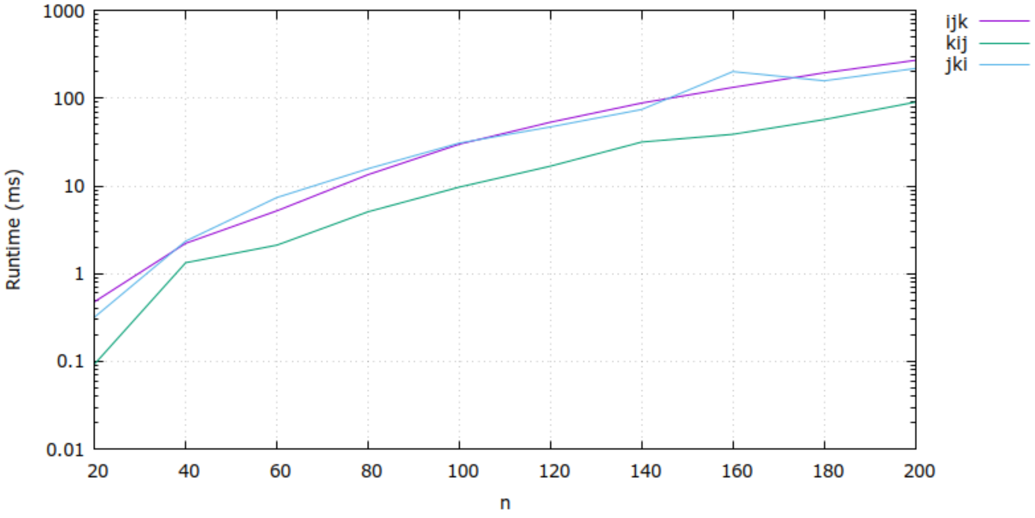
- 2 loads, 1 store
- 0.25 misses/iter

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

jki and kji (inner loop):

- 2 loads, 1 store
- 2 misses/iter

On a real machine



Summary

- Memory hierarchies are part of all nontrivial systems.
- Cache misses have dramatic impact on performance.
- Significant speedup can be achieved just by permuting loops.