

Cache memory

course “Essentials of computing systems”

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contents

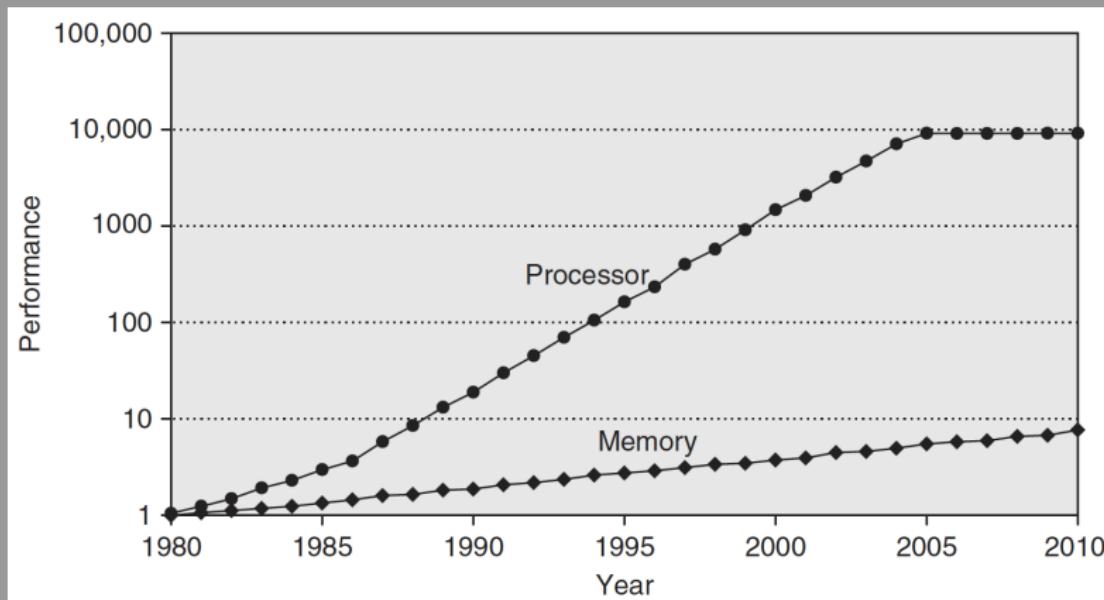
- 1 Main principles
- 2 Mapping function
- 3 Replacement algorithm

contents

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- 2 Mapping function
- 3 Replacement algorithm

processor-memory performance gap

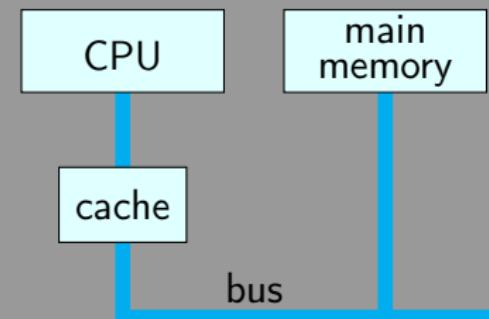
a.k.a. processor-memory bottleneck, memory wall, CPU-memory speed mismatch



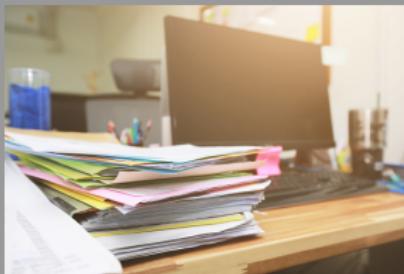
Hennessy and Patterson, Computer architecture: A quantitative approach, 5th ed., Morgan Kaufmann, 2012.

CPUs faster than memories

- Whenever the CPU needs to access the main memory, it must wait for many CPU cycles.
- This degrades the performance of the computer.
- A typical solution to the processor-memory gap is to design a computer to have **cache memory**.
- Caches are designed to combine the access time of expensive and fast memory with the large size of cheap but slow memory.
- The cache speeds up memory accesses by storing recently used data closer to the CPU, instead of storing it in the memory.
- Cache memory is a small, high-speed type of memory that serves as a buffer for frequently accessed data.



non-computer examples



definition

- cache: high-speed memory used to store frequently accessed or recently accessed data and instructions, so that future requests for that data/instructions can be provided faster.
- Caching is the storage of **duplicate** copies of digital information in places that are **local**, **fast**, and convenient so that the data can be accessed **quickly** if needed again rather than retrieved from the ultimate source.

cache principle

- main principle: the most frequently requested memory words are stored in the cache.
- Whenever the CPU needs a given word, it first looks in the cache.
- Most of the times, the needed word is expected to be in the cache.
- If this is not the case, then the CPU must access the main memory to get it.
- If a substantial percentage of the words are in the cache, the average access time is greatly reduced.

locality

- The success of the cache in reducing the accesses to the memory depends on what fraction of the words are in the cache.
- The fact that programs do not access the memory completely in an arbitrary way favours the success of caches.
- The use of the memory has some degree of predictability.
- An important observation related to the execution of programs is the **principle of locality**.
- Programs tend to reuse data and instructions that were recently used.
- Many programs spend 90% of their execution times in 10% of the code.

locality

- One can predict which instructions and pieces of data are to be used in the near future based on the most recent accesses.
- This locality principle has two different types:
 - **temporal locality** – recently accessed data or instructions are likely to be needed in the near future;
 - **spatial locality** – items whose memory addresses are close to each other tend to be referenced close together in time.
- These two types of locality are observed during the execution of a loop that accesses all the elements of an array.
- This principle also applies to code, as instructions, by default, are fetched from consecutive positions in the memory.
- Most program execution time is spent in loops, in which the same instructions are repeatedly executed.

cache miss

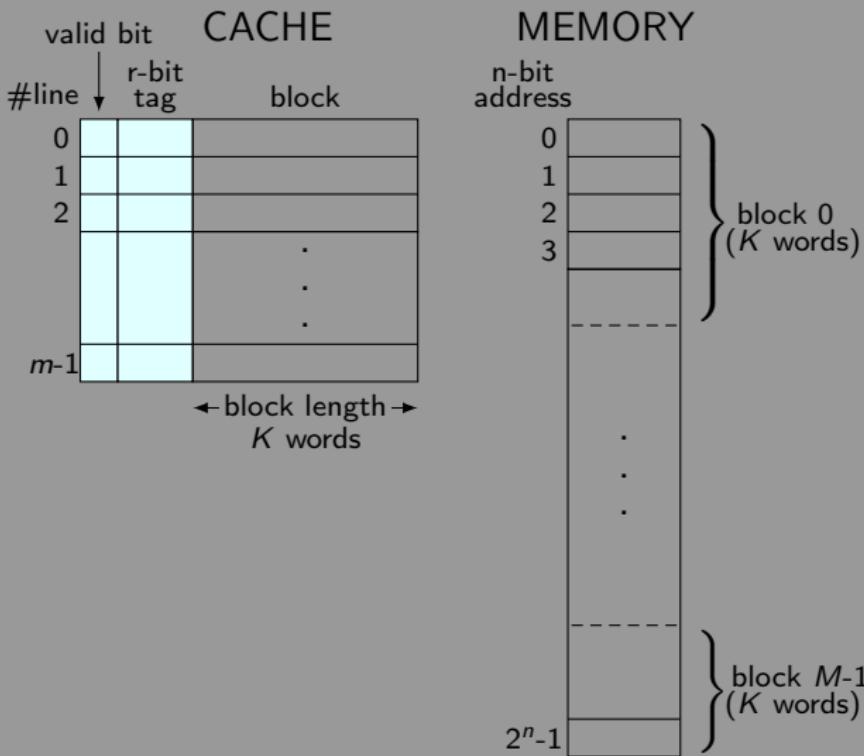
- Whenever the processor fails to obtain a given word from the cache (**cache miss**), the word must be read from memory.
- To take advantage of locality, the word and its neighbours are brought from the main memory into the cache.
- It is likely that many of the neighbours will be needed shortly.
- This approach is more efficient than fetching individual words, as it is faster to fetch n words at once than one word n times.

hit rate and miss rate

- A **cache hit** occurs when the requested data is located in the cache.
- With the number of hits and misses, it is possible to calculate the **hit rate** and the **miss rate**.
- They are the percentages of memory accesses found and not found, respectively, in the cache, during the execution of a program.
- The time required to fetch the requested data in the cache is designated as **hit time**.
- The **miss penalty** is the time required to process a miss, which includes substituting a block in the cache and the additional time to deliver the requested data to the processor.
- The time to process a hit is significantly smaller than the time to process a miss.

cache block and line

- A **cache block** is the minimum unit of transfer between the cache and the main memory.
- This term also refers to the physical location in the main memory and in the cache.
- A **cache line** is the portion of the cache memory that can store one block.
- A line contains control information, including:
 - a **tag** that identifies the memory address of the block stored in that line;
 - a **valid bit** to signal whether the data in the line is valid or not.
- When the system is booted, all cache lines are obviously marked as not valid.



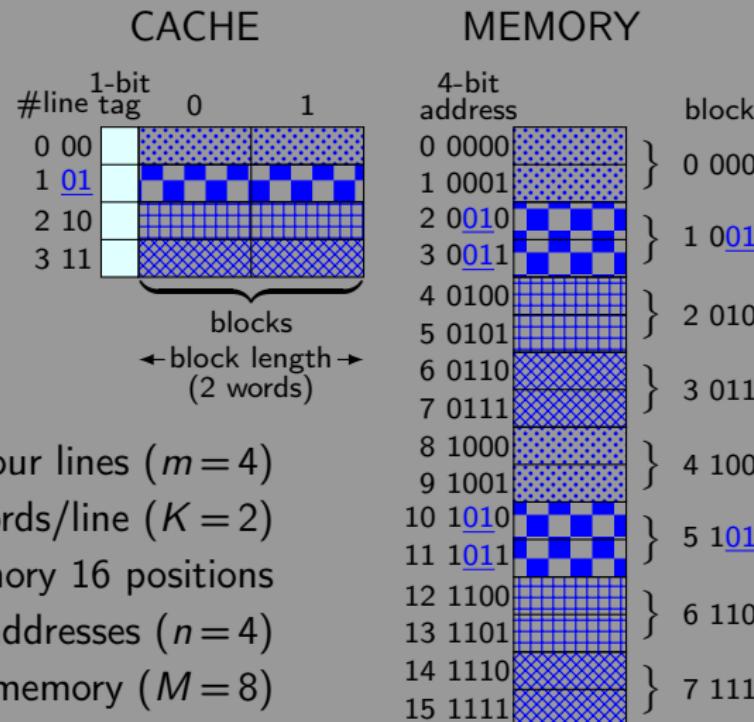
contents

- 1 Main principles
- 2 Mapping function
- 3 Replacement algorithm

content-addressable memory

- Caches are not accessed by address, but instead by content.
- Cache is often called **content-addressable memory (CAM)**.
- Both (part of) the address and the contents are stored.
- When a given memory address is being requested, all cache entries must be searched to check if it is stored there.
- When the address matches, its content is fetched from the cache memory.
- One needs a mechanism for determining which specific main memory block currently occupies a cache line.
- The selection of the mapping function determines how the cache is logically organised.
- Three mapping techniques are usually adopted: direct, associative, and set-associative.

direct mapping



direct mapping

- Direct mapping maps each block of main memory into only one possible cache line.
- The number of the cache line $i = j \bmod m$, where j is the memory block number.
- The memory block number is given by the memory address but ignoring the $\log_2 K$ LSBs.
- The mapping is expressed as $i = j \bmod 4$.
- Blocks 0 and 4 map to line 0, blocks 1 and 5 to line 1, ...
- The two last bits of the block number indicate the cache line.
- The MSB of the block number is stored in the tag of the cache line, to identify which block is stored there.
- Blocks $0, m, 2 \cdot m, \dots$ map to line 0.
- Blocks $1, m+1, 2 \cdot m+1, \dots$ map to line 1, ...

direct mapping

- The direct mapping function can be implemented using the main memory address.
- For the purpose of cache access, each main memory address can be viewed as consisting of three fields:
 - ① The o LSBs identify a unique word or byte within a memory block ($o = \log_2 K$).
 - ② The next s bits specify part of the block number ($s = \log_2 m$).
 - ③ The remaining t bits are saved in the tag ($t = n-s-o$).
- $o = \log_2 2 = 1$, $s = \log_2 4 = 2$, and $t = 4-2-1 = 1$.

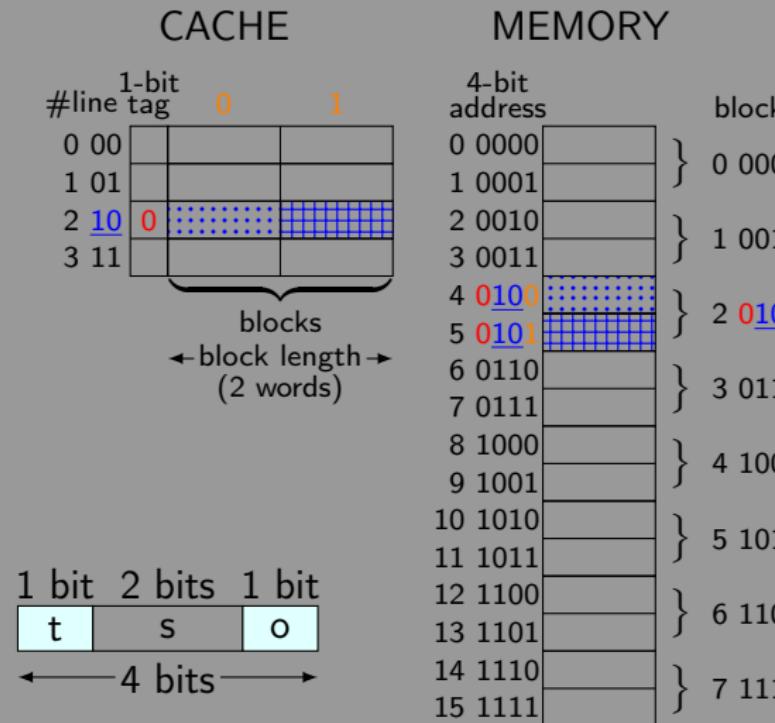
1 bit	2 bits	1 bit
t	s	o

↔ 4 bits →

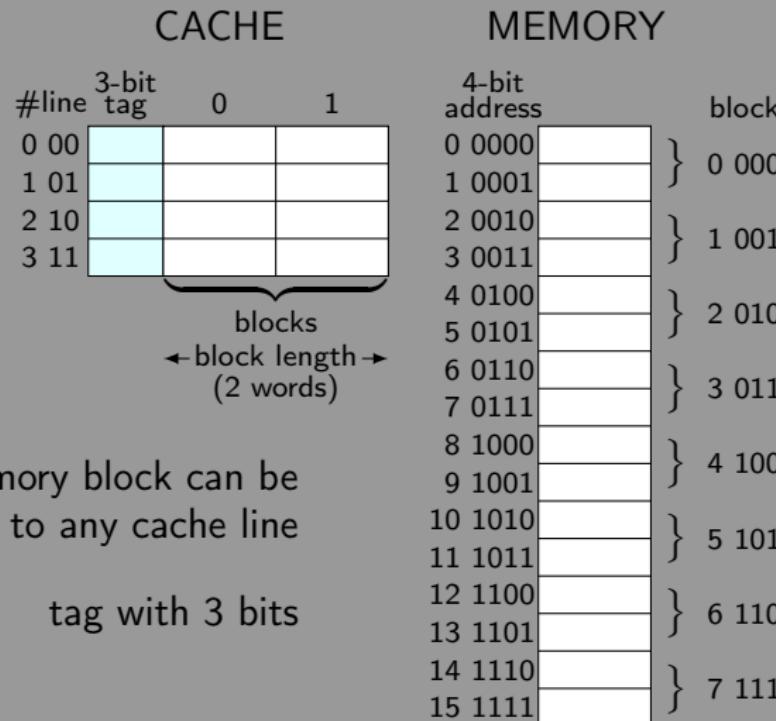
t	s	o
1	1	0

mapped to cache line 10_2
tag is 1

direct mapping

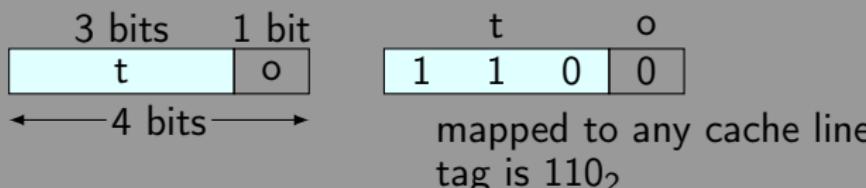


fully associative mapping

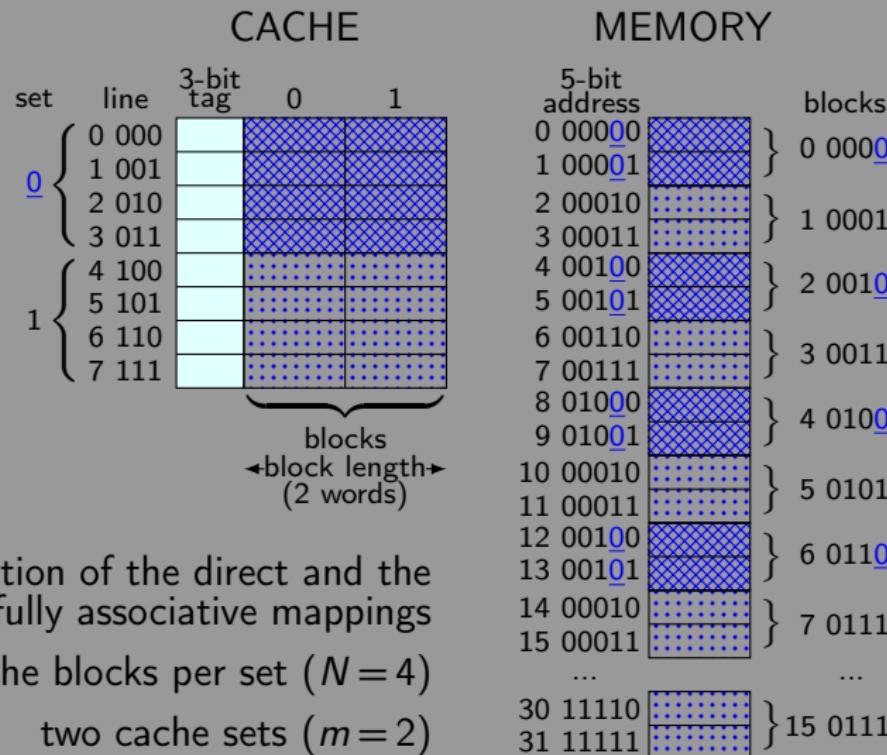


fully associative mapping

- For the purpose of cache access, each main memory address can be viewed as consisting of two fields:
 - The o LSBs identify a unique word or byte within a memory block ($o = \log_2 K$).
 - The remaining t bits are saved in the tag ($t = n - o$).
- $o = \log_2 2 = 1$ and $t = 4 - 1 = 3$.

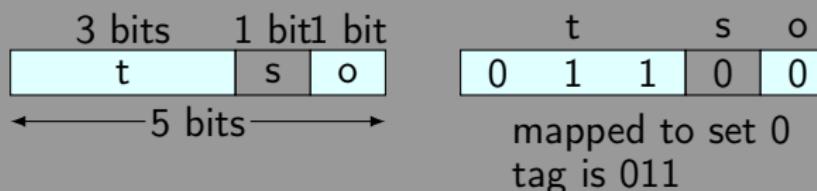


set associative mapping

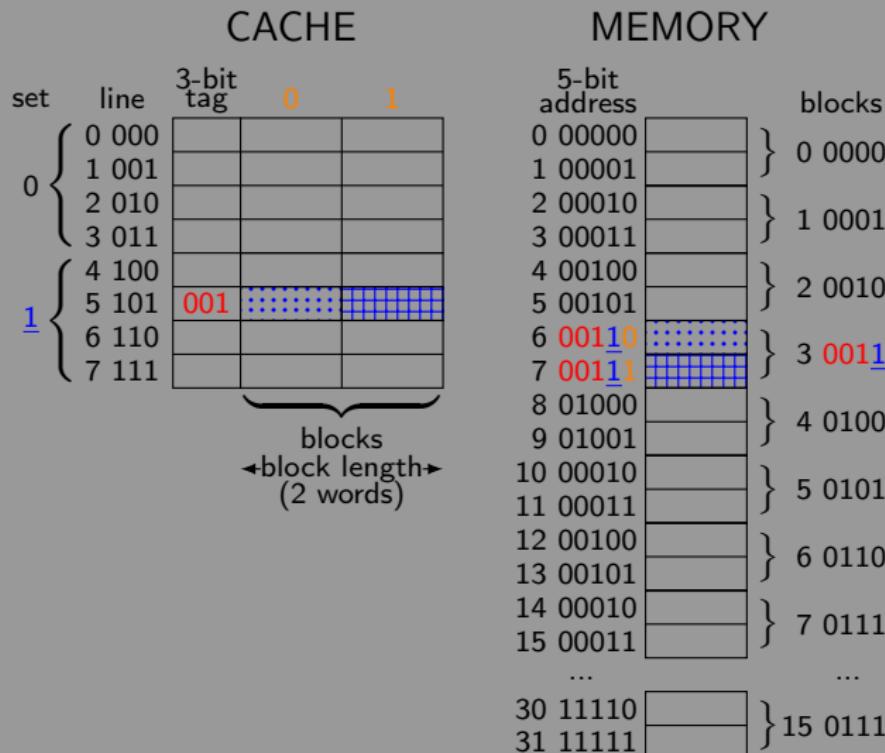


set associative mapping

- Direct mapped cache can be seen as a special case of N-way set associative cache mapping where the set size is one ($N=1$).
- The 2-way set associative mapping function can be implemented using the main memory address.
- Each memory address can be viewed as consisting of three fields:
 - ① The o LSBs identify a unique word or byte within a memory block ($o = \log_2 K$).
 - ② The next s bits specify the set number ($s = \log_2 m$).
 - ③ The remaining t bits are saved in the tag ($t = n-s-o$).
- $o = \log_2 2 = 1$, $s = \log_2 2 = 1$, and $t = 5-1-1 = 3$.



set associative mapping



contents

- 1 Main principles
- 2 Mapping function
- 3 Replacement algorithm

replacement

- In a direct-mapped cache, if there is contention for a cache block, there is only one possible action.
- The existing block is removed from the cache to make room for the new block.
- This process is called **replacement**.
- With direct mapping, there is no need for a sophisticated replacement algorithm.
- With direct mapping, if a block is about to be replaced, it should be updated in the main memory if it has been modified after being loaded into the cache.
- The **dirty bit** is a control flag associated with each cache line to indicate whether the data stored has been modified, since it was last loaded from main memory.

replacement algorithm

- For associative mappings, whenever the cache is full and a new block needs to be stored, a **replacement algorithm** is needed.
- It decides in which cache line to store the new block.
- Many alternatives exist for this algorithm.
- If temporal locality is considered, it is likely that any value that has not been used recently will not be needed again soon.
- If one registers the time a cache line is accessed, one can select for replacement the line that has been used least recently.
- This is the **least recently used (LRU)** algorithm, which requires to keep a history of accesses for every cache line.

replacement algorithm

- Another possible approach is the **first in first out (FIFO)** strategy.
- The block that has been in cache the longest is selected as the one to be replaced by the new block.
- Another alternative is to randomly select the cache line to be replaced.
- A possible option is the **not most-recently used (NMRU)** policy that randomly chooses among all blocks but the one most recently referenced.
- The **least frequently used (LFU)** policy replaces the block that has been referenced the fewest number of times.
- The algorithm selected by the computer architects often depends on how the system is to be used.
- This selection is not trivial as no single algorithm is the best for all contexts.