Computer Organization and Architecture

Memory System Design

(Date: 07/02/2023)

Virtual Memory :-

- The concept of virtual memory is in principle similar to that of the cache memory
- A virtual memory system attempts to optimize the use of the main memory (the higher speed portion)
- Usually available physical memory space is not enough to host all the parts of a given active program
- Those parts of the program which are currently active → brought to the main memory
- Parts that are not active will be stored on the magnetic disk
- If the segment of the program containing the word requested by the processor is not in the main memory at the time of the request, then such segment will have to be brought from the disk to the main memory

Ref: Fundamentals Of Computer Organization and Architecture__ Mostafa Abd-El-Barr and Hesham El Rewini

- Movement of data between the disk and the main memory takes the form of pages
- A page is a collection of memory words, which can be moved from the disk to the MM when the processor requests accessing a word on that page
- A typical size of a page in modern computers ranges from 2K to 16K bytes
- A page fault occurs when the page containing the word required by the processor does not exist in the MM and has to be brought from the disk

- A cache miss can cause a time penalty that is 5 to 10 times as costly as a cache hit
  A page fault, on the other hand can be 1000 times as costly as a page hit

- It is therefore not reasonable to have the processor wait on a page fault while a page is being transferred to the main memory

- Virtual (logical) Address : the address issued by the processor in order to access a given word does not correspond to the physical memory space
- The memory management unit (MMU) is responsible for the translation of virtual addresses to their corresponding physical addresses
- Three address translation techniques can be identified
- These are direct-mapping, associative-mapping, and set-associative-mapping
- In all these techniques, information about the main memory locations and the corresponding virtual pages are kept in a table called the page table
- The page table is stored in the main memory
- Other information kept in the page table includes a bit indicating the validity of a page, modification of a page, and the authority for accessing a page

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- The **valid bit** is set → if the corresponding page is actually loaded into the main memory
- Valid bits for all pages are reset when the computer is first powered on
- The other control bit that is kept in the page table is the **dirty bit**
- It is set → if the corresponding page has been altered while residing in the main memory
- While residing in the main memory, if a given page has not been altered, then its dirty bit will be reset

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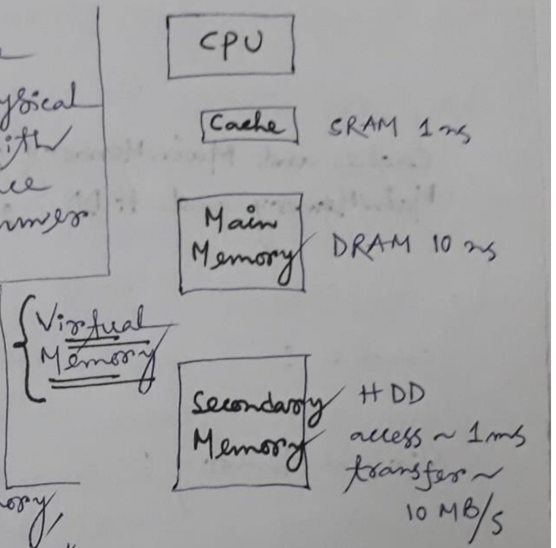
[Virtual Memory objectives] :~

↳ To overcome the limitations of physical memory size, with least inconvenience to the programmer



↳ Programmer does not bother about moving code & data between disk and main memory, as opposed to "overlays".

↳ To allow multiple programs to share memory without interference

Virtual Memory

↳ An ~~ithe~~ illusion of a memory much larger than the ~~physical~~ Main Memory

↳ Large virtual address space, in spite of limited Main Memory address

↳ Both spaces divided into equal sized pages

↳ Each virtual page has a place on the disk

↳ Some of these may also be in the Main Memory

[Virtual Memory v/s. Cache]

↳ Though similar, there are differences

↳ Speed difference

Cache and **Main Memory** : ~1 order of magnitude

Main Memory and **HDD** : ~ Several orders " "

↳ Response to a miss

cache : must be handled by h/w, can not afford to switch context

Virtual Memory : can not keep CPU waiting, must switch context, can be conveniently handled by s/w

↳ Terminology differences

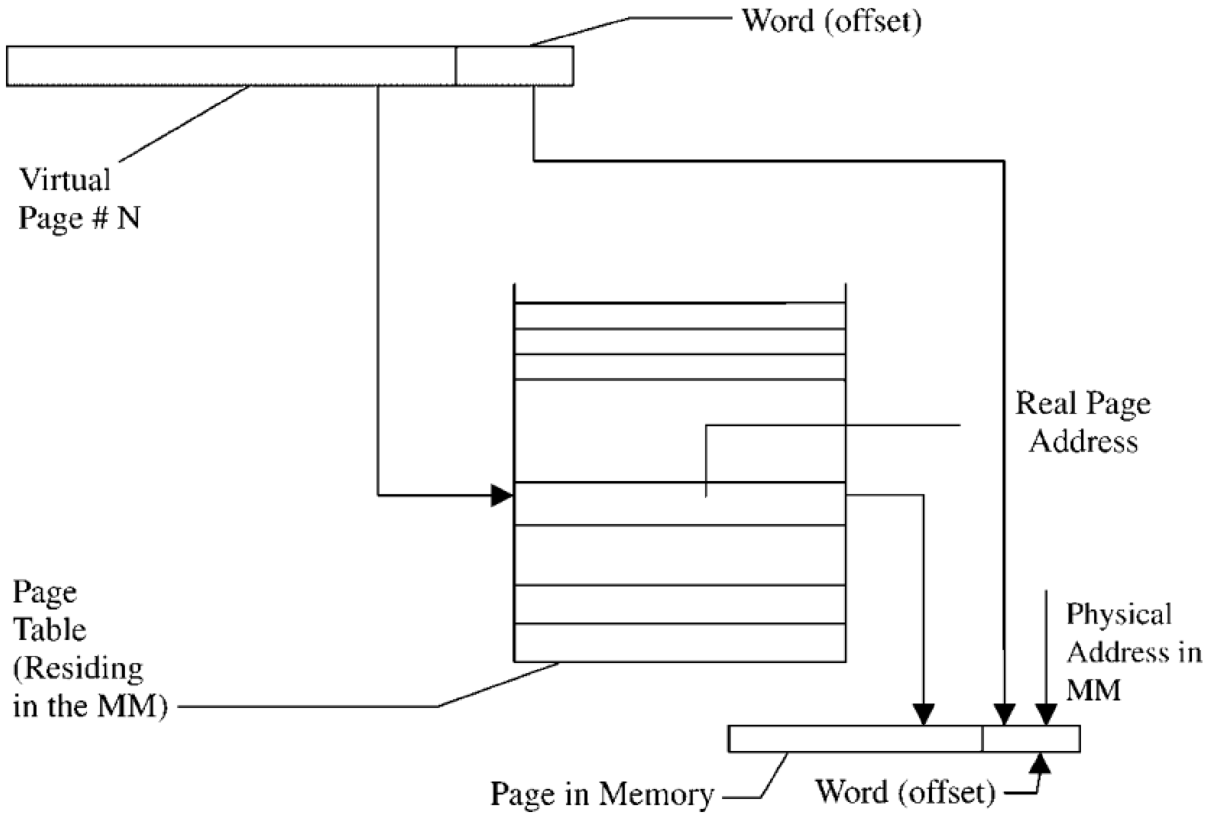
Cache : block, miss, cache directory

Virtual Memory : Page, Page fault, Page table

↳ miss rate

Virtual Memory can only afford extremely low miss rates

Direct-mapping virtual address translation



- The virtual address issued by the processor is divided into two fields: **the <u>virtual page number</u> and the <u>offset fields</u>**
- If the number of bits in the virtual page number field is N, then the number of entries in the page table will be 2^N
- The virtual page number field is used to directly address an entry in the page table

✓ If the corresponding page is valid (as indicated by the valid bit), then the contents of the specified page table entry will correspond to the physical page address

✓ The latter is then extracted and concatenated with the offset field in order to form the physical address of the word requested by the processor

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- If, on the other hand, the specified entry in the page table does not contain a valid physical page number then this represents a page fault

- In this case, the MMU will have to bring the corresponding page from the hard disk, load it into the main memory, and indicate the validity of the page

- The translation process is then carried out as explained before

- The main advantage of the direct-mapping technique is its simplicity measured in terms of the direct addressing of the page table entries

- Its main disadvantage is the expected large size of the page table

- In order to overcome the need for a large page table, the associative-mapping technique is used

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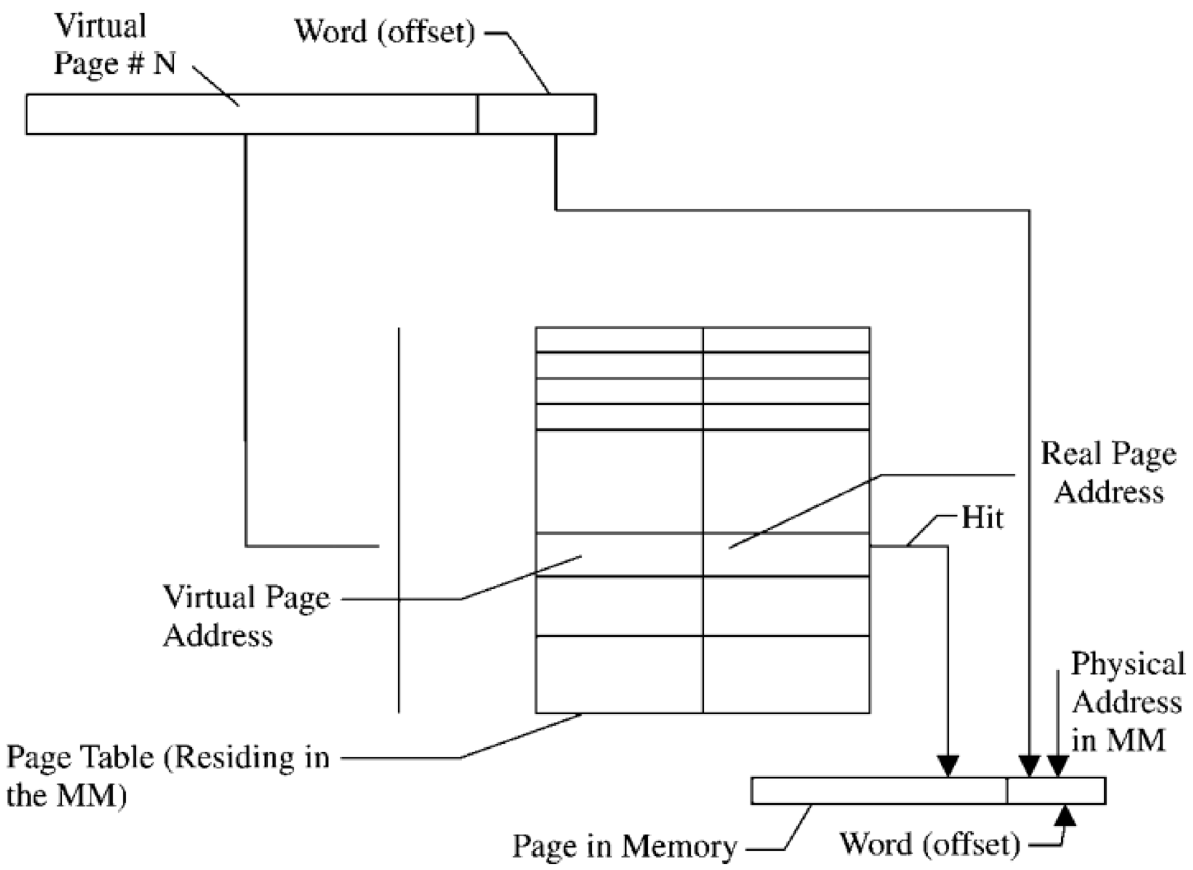
Associative mapping address translation



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- The technique is similar to direct mapping The virtual address issued by the processor is divided into two fields: the virtual page number and the offset fields
- However, the page table used in associative mapping could be far shorter than its direct mapping counterpart

✓ Every entry in the page table is divided into two parts: the virtual page number and the physical page number

✓ A match is searched (associatively) between the virtual page number field of the address and the virtual page numbers stored in the page table

- If a match is found, the corresponding physical page number stored in the page table is extracted and is concatenated with the offset field in order to generate the physical address of the word requested by the processor

- If, on the other hand, a match could not be found then this represents a page fault

- In this case, the MMU will have to bring the corresponding page from the hard disk, load it into the main memory, and indicate the validity of the page. The translation process is then carried out as explained before

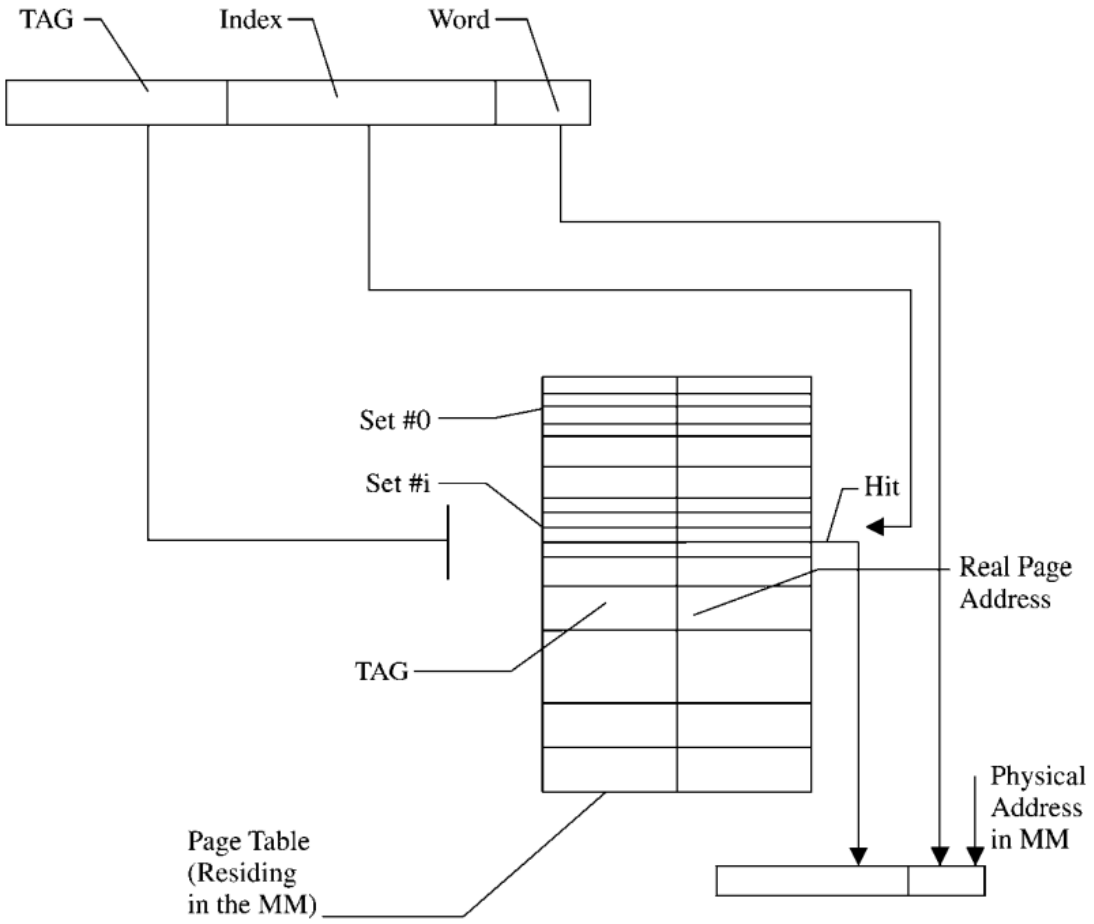
- The main advantage of the associative-mapping technique is the expected shorter page table (compared to the direct-mapping technique) required for the translation process

- Its main disadvantage is the search required for matching the virtual page number field and all virtual page numbers stored in the page table

- Although such a search is done associatively, it requires the use of an added hardware overhead

Ref: Fundamentals Of Computer Organization and Architecture__ Mostafa Abd-El-Barr and Hesham El Rewini

Set-associative mapping address translation



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- In this case, the virtual address issued by the processor is divided into three fields: the tag, the index, and the offset
- The page table used in set-associative mapping is divided into sets, each consisting of a number of entries
- Each entry in the page table consists of a tag and the corresponding physical page address

✓ Similar to direct mapping, the index field is used to directly determine the set in which a search should be conducted

✓ If the number of bits in the index field is S, then the number of sets in the page table should be 2^S

✓ Once the set is determined, then a search (similar to associative mapping) is conducted to match the tag field with all entries in that specific set

Replacement Algorithms (Policies)

- ✓ Basic to the implementation of virtual memory is the concept of demand paging
- ✓ This means that the operating system, and not the programmer, controls the swapping of pages in and out of main memory as they are required by the active processes
- ✓ When a process needs a nonresident page, the operating system must decide which resident page is to be replaced by the requested page
- ✓ The technique used in the virtual memory that makes this decision is called the replacement policy
- ✓ There exists a number of possible replacement mechanisms
- ✓ The main objective in all these mechanisms is to select for removal the page that expectedly will not be referenced in the near future

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Random Replacement

- ✓ According to this replacement policy, a page is selected randomly for replacement
- ✓ This is the simplest replacement mechanism
- ✓ It can be implemented using a pseudo-random number generator that generates numbers that correspond to all possible page frames

First-In-First-Out (FIFO) Replacement

- ✓ According to this replacement policy, the page that was loaded before all the others in the main memory is selected for replacement
- ✓ The basis for page replacement in this technique is the time spent by a given page residing in the main memory regardless of the pattern of usage of that page
- ✓ This technique is also simple
- ✓ However, it is expected to result in acceptable performance (measured in terms of the main memory hit ratio) if the page references made by the processor are in strict sequential order

Least Recently Used (LRU) Replacement

- ✓ According to this technique, page replacement is based on the pattern of usage of a given page residing in the main memory regardless of the time spent in the main memory
- ✓ The page that has not been referenced for the longest time while residing in the main memory is selected for replacement
- ✓ The LRU technique matches most programs' characteristics and therefore is expected to result in the best possible performance in terms of the main memory hit ratio

Clock Replacement Algorithm

- ✓ This is a modified FIFO algorithm
- ✓ It takes into account both the time spent by a page residing in the main memory (similar to the FIFO) and the pattern of usage of the page (similar to the LRU)
- ✓ The technique is therefore sometimes called the First-In-Not-Used-First-Out (FINUFO)
- ✓ In keeping track of both the time and the usage, the technique uses a pointer to indicate where to place the incoming page and a used bit to indicate the usage of a given page

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Segmentation

- There is another way in which addressable memory can be subdivided, known as segmentation
- Whereas paging is invisible to the programmer and serves the purpose of providing the programmer with a larger address space, segmentation is usually visible to the programmer and is provided as a convenience for organizing programs and data and as a means for associating privilege and protection attributes with instructions and data
- Segmentation allows the programmer to view memory as consisting of multiple address spaces or segments
- Segments are of variable, indeed dynamic, size
- Typically, the programmer or the OS will assign programs and data to different segments
- There may be a number of program segments for various types of programs as well as a number of data segments
- Each segment may be assigned access and usage rights
- Memory references consist of a (segment number, offset) form of address

Ref: Computer Organization and Architecture Designing for Performance__ William Stallings