

COMPUTER ORGANIZATION AND ARCHITECTURE

Course Code : CSE 2151

Credits : 04



MODULE 5: THE MEMORY SYSTEM

- Overview
 - Basic memory circuits
 - Organization of the main memory
 - Cache memory concept
 - Virtual memory mechanism
 - Secondary storage

SOME BASIC CONCEPTS

- Traditional Architecture

- If MAR is k bits long and MDR is n bits long, then memory will contain up to 2^k addressable locations and n -bits of data are transferred between the memory and processor.
- MFC: Memory Function Complete.

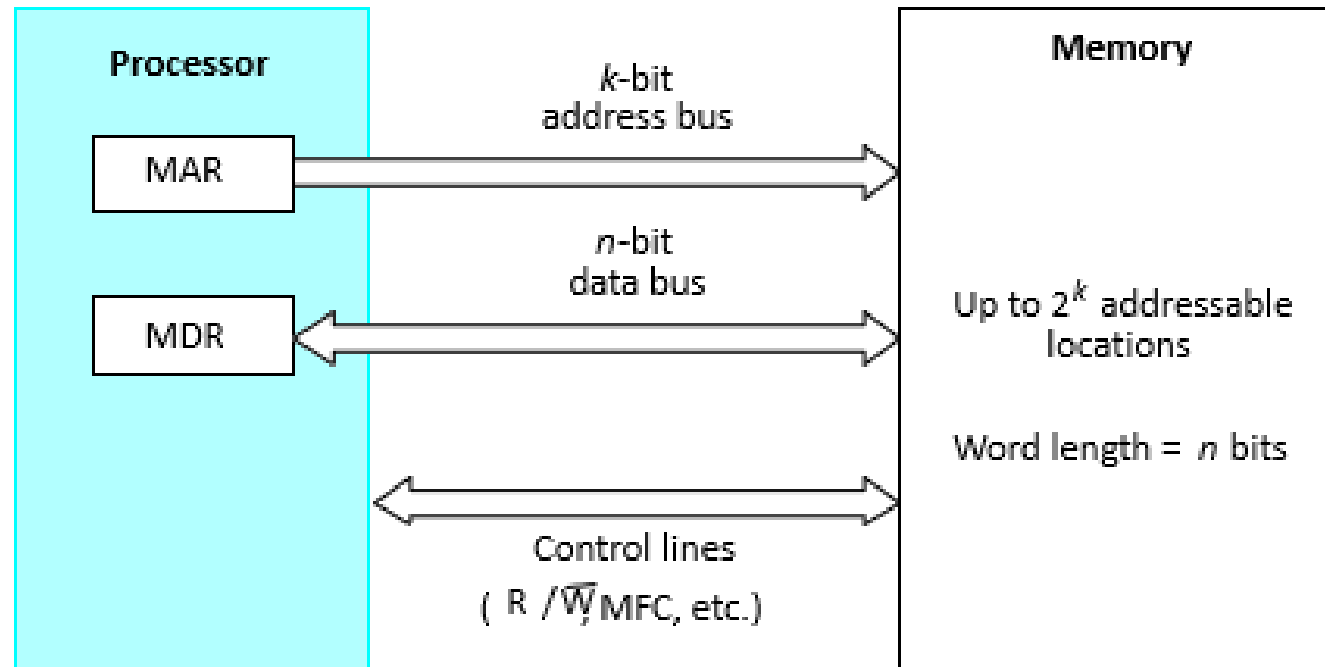


Figure 5.1. Connection of the memory to the processor.

SOME BASIC CONCEPTS

- “Block transfer”:
 - bulk data transfer
- Memory access time:
 - time that elapses between the initiation of an operation to transfer a word of data and the completion of that operation.
- Memory cycle time:
 - the minimum time delay required between the initiation of two successive memory operations
- RAM:
 - any location can be accessed for a Read or Write operation in some fixed amount of time that is independent of the location's address
- Cache memory
 - a small, fast memory inserted between the larger, slower main memory and the processor.
 - It holds the currently active portions of a program and their data.
- Virtual memory:
 - only the active portions of a program are stored in the main memory, and the remainder is stored on the much larger secondary storage device.
 - Sections of the program are transferred back and forth between the main memory and the secondary storage device in a manner that is transparent to the application program.
 - the application program sees a memory that is much larger than the computer's physical main memory
 - memory management unit

SEMICONDUCTOR RAM MEMORIES

- Internal Organization of Memory Chips
 - 16 words of 8 bits each: 16x8 memory org.
 - It has 16 external connections: addr. 4, data 8, control: 2, power/ground: 2
 - 1K memory cells: 128x8 memory, external connections: ? 19(7+8+2+2)
 - 1Kx1:?

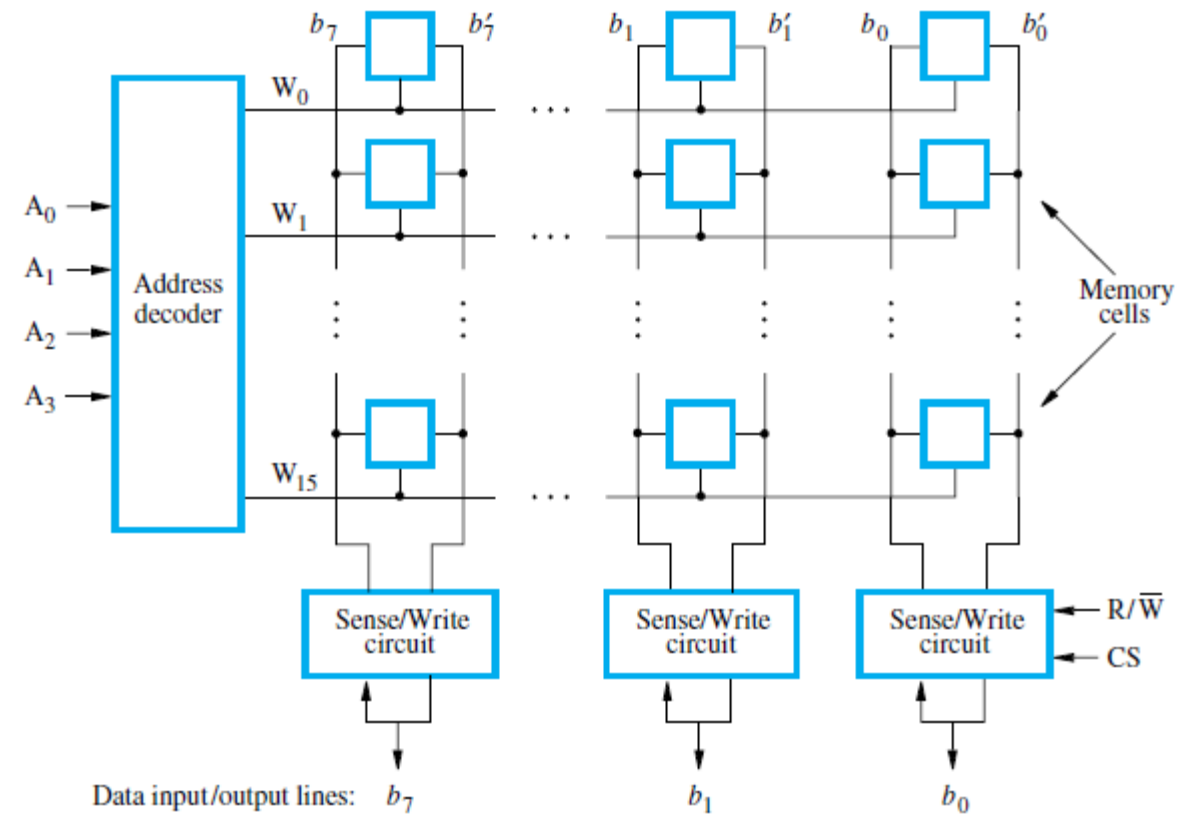
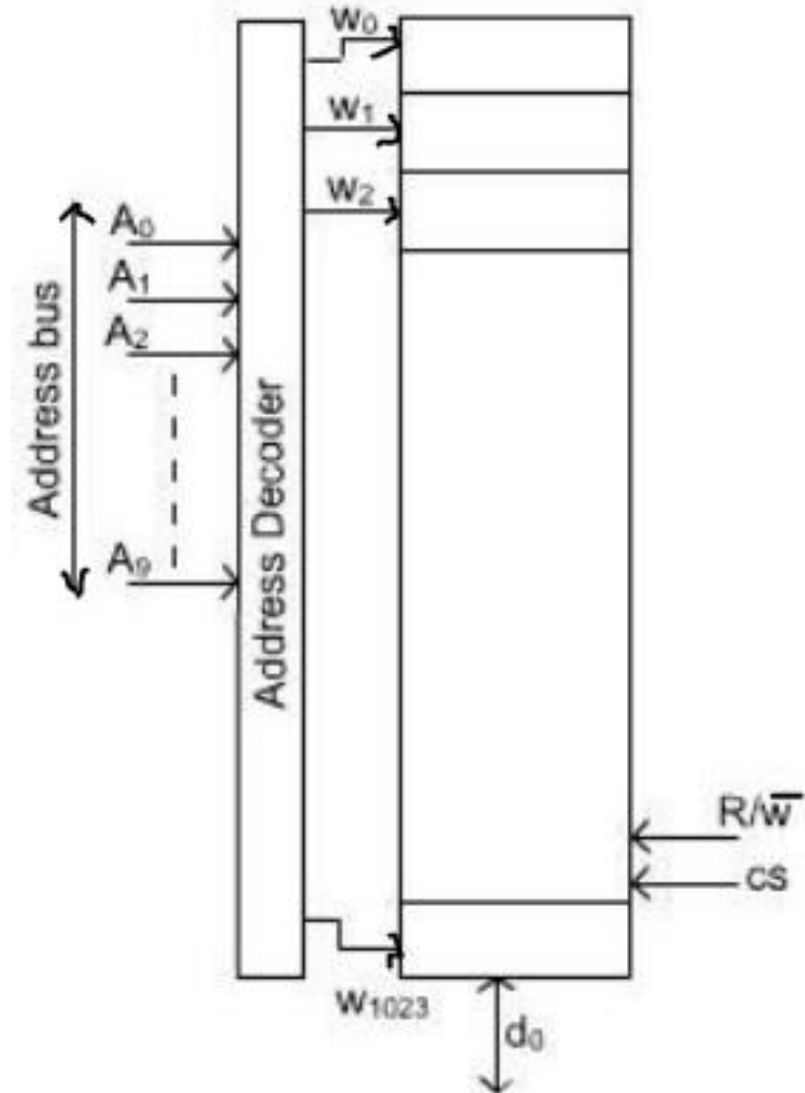


Figure 8.2 Organization of bit cells in a memory chip.

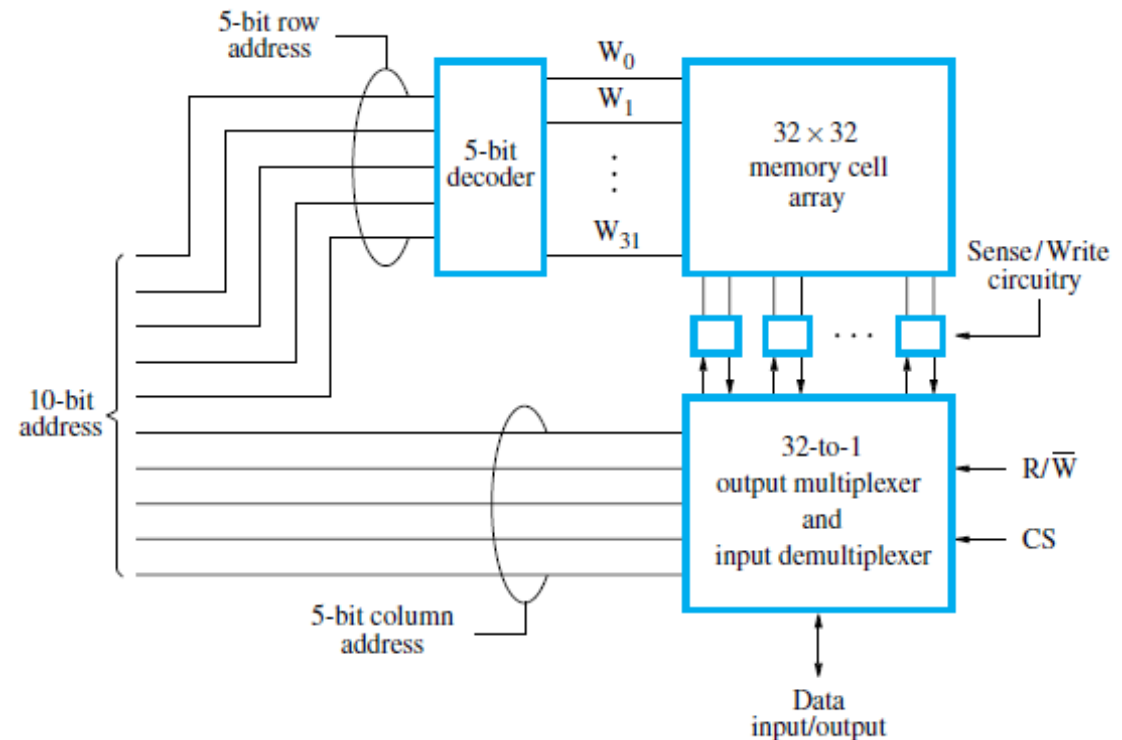
SEMICONDUCTOR RAM MEMORIES

- Internal Organization of Memory Chips
 - 1Kx1: Meaning 1024 words X 1 bit organization,.



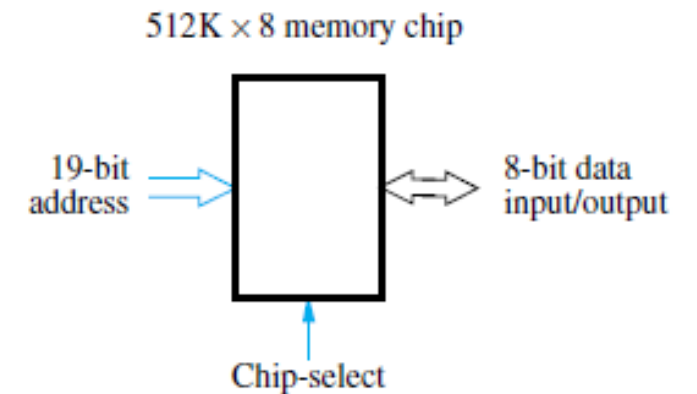
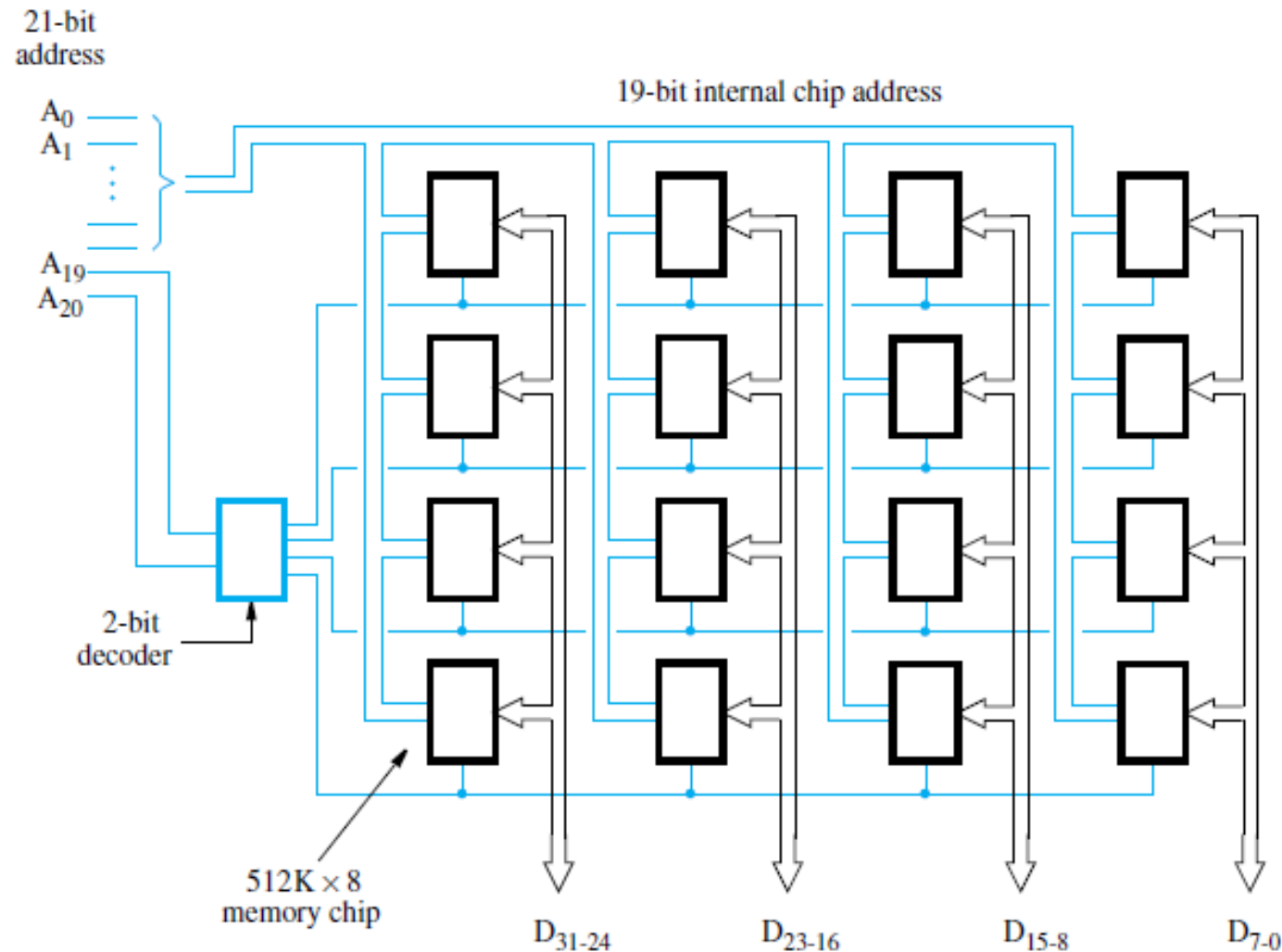
SEMICONDUCTOR RAM MEMORIES

- 1Kx1:
 - If several memory words are organized in one row, then address bus is divided into two groups: one forms the row address, and the other forms the column address.
 - The 10-bit address is divided into 5 bits each to form the row and column address of the cell array.
 - A row address selects a row of 32 cells, all of which are accessed in parallel. However, according to the column address, only one of these cells is connected to the external data line via the input output multiplexers.
- 15 (10+1+2+2)



STRUCTURE OF LARGER MEMORIES

- Organization of a $2M \times 32$ memory module using $512K \times 8$ static memory chips.



MEMORY HIERARCHY: SPEED, SIZE, AND COST

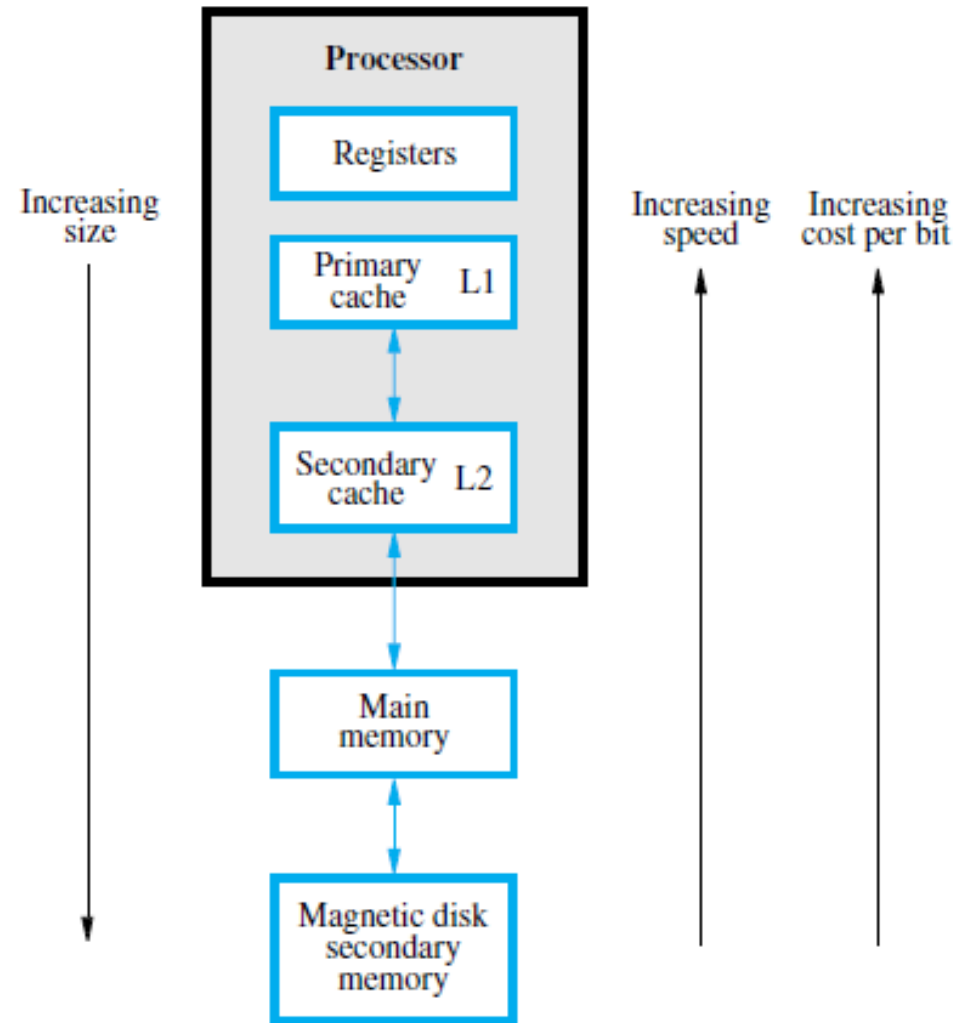


Figure 8.14 Memory hierarchy.

CACHE MEMORIES

- What is cache?
- Why we need it?
- Locality of reference
 - temporal- a recently executed instruction is likely to be executed again very soon.
 - spatial- instructions close to a recently executed instruction are also likely to be executed soon
- Cache block – cache line
 - A set of contiguous address locations of some size

CACHE MEMORIES

- Mapping function
- Replacement algorithm
- Hit / miss
- Write-through / Write-back
- Load through

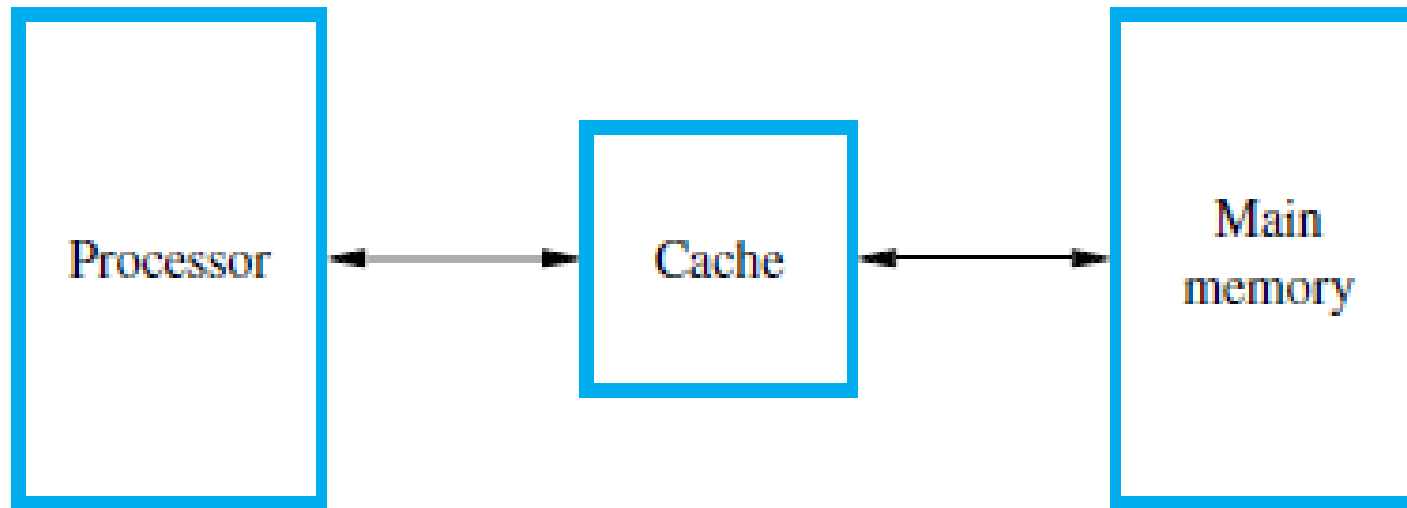


Figure 8.15 Use of a cache memory.

CACHE MEMORIES

- The correspondence between the main memory blocks and those in the cache is specified by a mapping function.
- When the cache is full and a memory word (instruction or data) that is not in the cache is referenced, the cache control hardware must decide which block should be removed to create space for the new block that contains the referenced word.
- The collection of rules for making this decision constitutes the cache's replacement algorithm.

CACHE HITS

- The cache control circuitry determines whether the requested word currently exists in the cache.
- If it does, the Read or Write operation is performed on the appropriate cache location. -a read or write hit.
 - main memory not involved when there is a cache hit in a Read operation
 - Write Operation –two ways
 - write-through protocol, both the cache location and the main memory location are updated.
 - write-back, or copy-back, protocol-update only the cache location and to mark the block containing it with an associated flag bit, often called the dirty or modified bit. The main memory location of the word is updated later

WRITE-THROUGH V/S WRITE-BACK

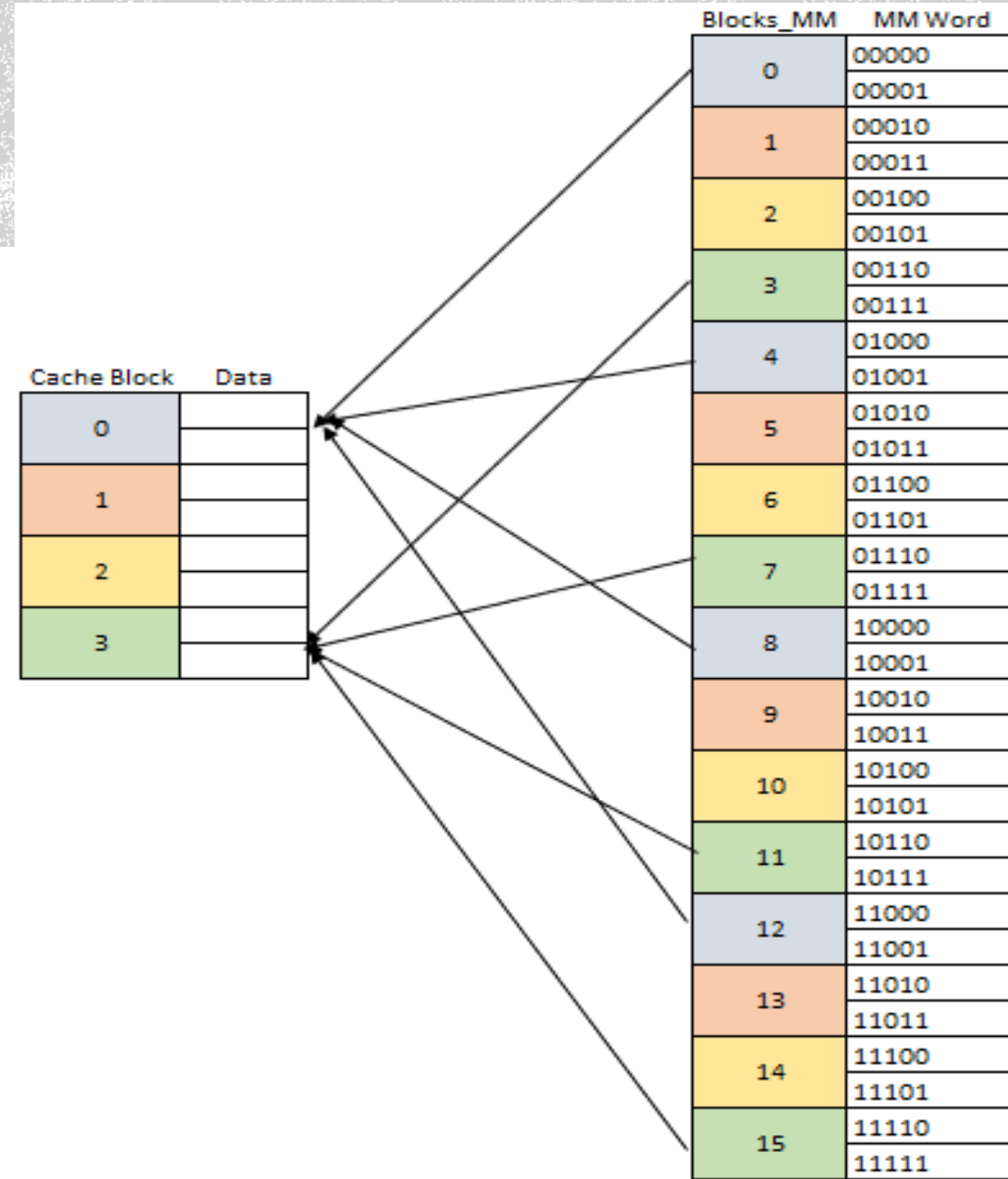
- The write-through protocol is simpler than the write-back protocol
 - But it results in unnecessary Write operations in the main memory when a given cache word is updated several times during its cache residency.
- The write-back protocol also involves unnecessary Write operations
 - Because all words of the block are eventually written back, even if only a single word has been changed while the block was in the cache.
- The write-back protocol is used most often, to take advantage of the high speed with which data blocks can be transferred to memory chips.

CACHE MISSES

- Read operation for a word that is not in the cache constitutes a Read miss.
- causes the block of words containing the requested word to be copied from the main memory into the cache.
- After the entire block is loaded into the cache, the word requested is forwarded to the processor.
- Alternatively, this word may be sent to the processor as soon as it is read from the main memory. The latter approach, which is called load-through, or early restart, reduces the processor's waiting time somewhat, at the expense of more complex circuitry.
- When a Write miss occurs in a computer that uses the write-through protocol, the information is written directly into the main memory.
- For the write-back protocol, the block containing the addressed word is first brought into the cache, and then the desired word in the cache is overwritten with the new information.

DIRECT MAPPING

- Block j of main memory maps onto block $j \bmod 3$ of the cache
- To select 1 of 2 word in each block: **1 bit**
- Identify the block among 4 blocks in the cache: **2 bits**
- Out of the 4 blocks in MM that maps to the cache memory, which one is currently residing in the cache? **2 bits** (Can also be calculated as $16/4=4$: 2 bits)
- Example: 11000
- Tag:** 11
- Block:** 00=0, in the 0th block of the cache
- Word:** 0=0, the 0th word of the 0th block in the cache



DIRECT MAPPING

- Block j of main memory maps onto block j modulo 128 of the cache
 - 4: to select one of 16 words. (each block has $16=2^4$ words)
 - 7: points to a particular block in the cache ($128=2^7$)
 - 5: 5 tag bits are compared with the tag bits associated with its location in the cache. Identify which of the 32 blocks that are resident in the cache ($4096/128$).
-
- Example: 11101,1111111,1100
 - Tag: 11101
 - Block: $1111111=127$, in the 127th block of the cache
 - Word: $1100=12$, the 12th word of the 127th block in the cache

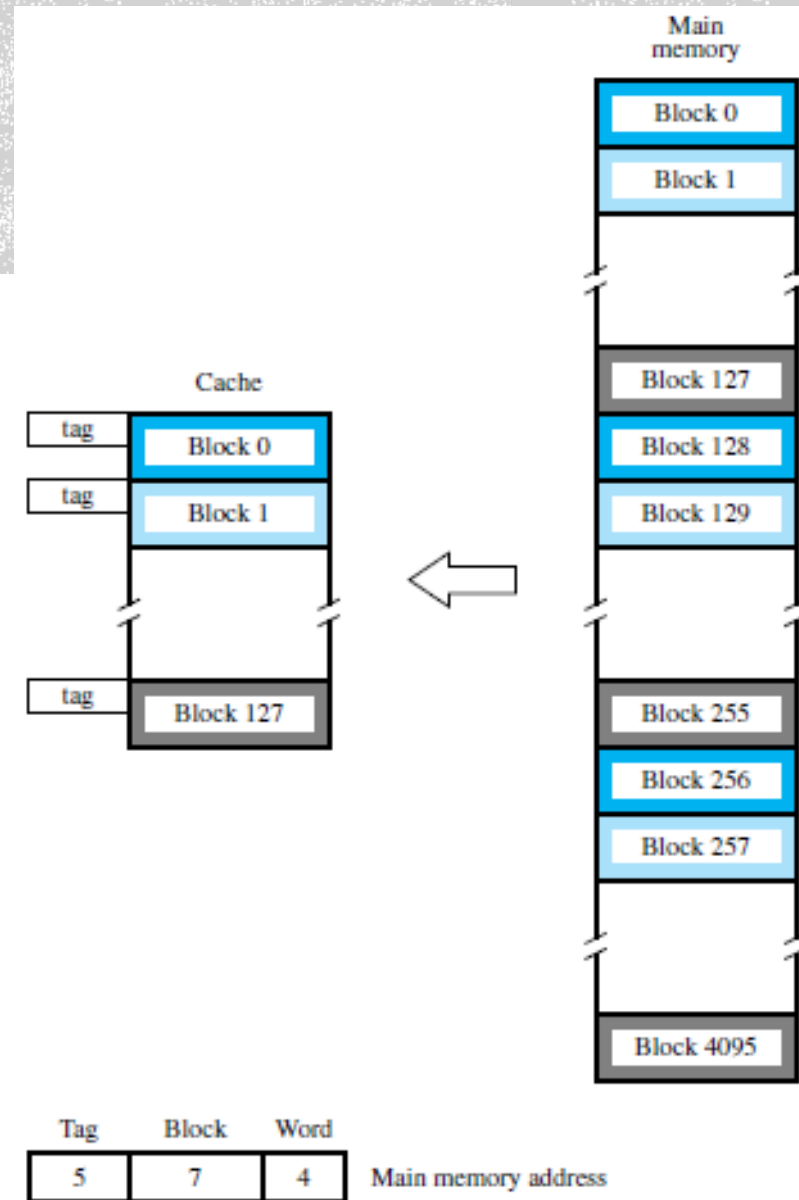


Figure 8.16 Direct-mapped cache.

ASSOCIATIVE MAPPING

- To select 1 of 2 word in each block: **1 bit**
- Identify which of the 16 blocks that are resident in the cache : **4 bits**
- Example: 11000
- **Tag:** 1100
- Word: 0=0, the 0th word of a block in the cache

Cache Block(0)	Data(1)
0	
1	
2	
3	

Blocks_MM	MM Word
0	00000 00001
1	00010 00011
2	00100 00101
3	00110 00111
4	01000 01001
5	01010 01011
6	01100 01101
7	01110 01111
8	10000 10001
9	10010 10011
10	10100 10101
11	10110 10111
12	11000 11001
13	11010 11011
14	11100 11101
15	11110 11111

ASSOCIATIVE MAPPING

- 4: one of 16 words. (each block has $16=2^4$ words)
- 12: 12 tag bits Identify which of the 4096 blocks that are resident in the cache $4096=2^{12}$.
- Example: 111011111111,1100
- Tag: 111011111111
- Word: 1100=12, the 12th word of a block in the cache

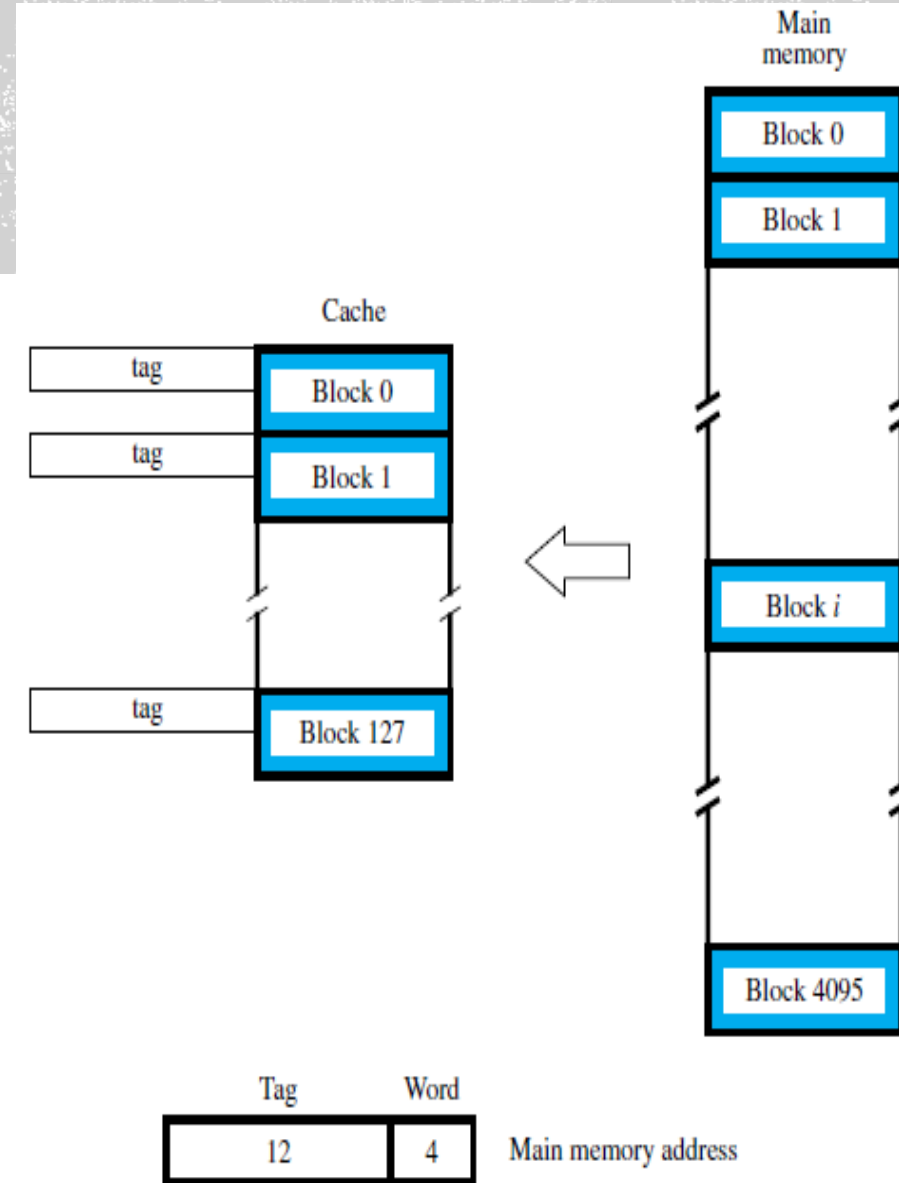


Figure 8.17 Associative-mapped cache.

SET ASSOCIATIVE MAPPING

- To select 1 of 2 word in each block: **1 bit**
- Identify the set among 2 sets in the cache: **1 bit**
- Out of the 8 blocks in MM that maps to the cache memory, which one is currently residing in the cache?
3 bits (Can also be calculated as $16/2=8$: 3 bits)
- Example: 11000
- **Tag:** 110
- **Set:** 0=0, in the 0th set of the cache
- **Word:** 0=0, the 0th word of the 0th set in the cache

Set	Cache Block	Data
0	0	
	1	
1	2	
	3	

Blocks_MMMM Word		
0000	0	00000
		00001
0001	1	00010
		00011
0010	2	00100
		00101
0011	3	00110
		00111
0100	4	01000
		01001
0101	5	01010
		01011
0110	6	01100
		01101
0111	7	01110
		01111
1000	8	10000
		10001
1001	9	10010
		10011
1010	10	10100
		10101
1011	11	10110
		10111
1100	12	11000
		11001
1101	13	11010
		11011
1110	14	11100
		11101
1111	15	11110
		11111

SET ASSOCIATIVE MAPPING

- 4: one of 16 words. (each block has $16=2^4$ words)
 - 6: points to a particular set in the cache ($128/2=64=2^6$)
 - 6: 6 tag bits is used to check if the desired block is present ($4096/64=64=2^6$).
-
- Example: 111011,111111,1100
 - Tag: 111011
 - Set: 111111=63, in the 63th set of the cache
 - Word: 1100=12, the 12th word of the 63th set in the cache

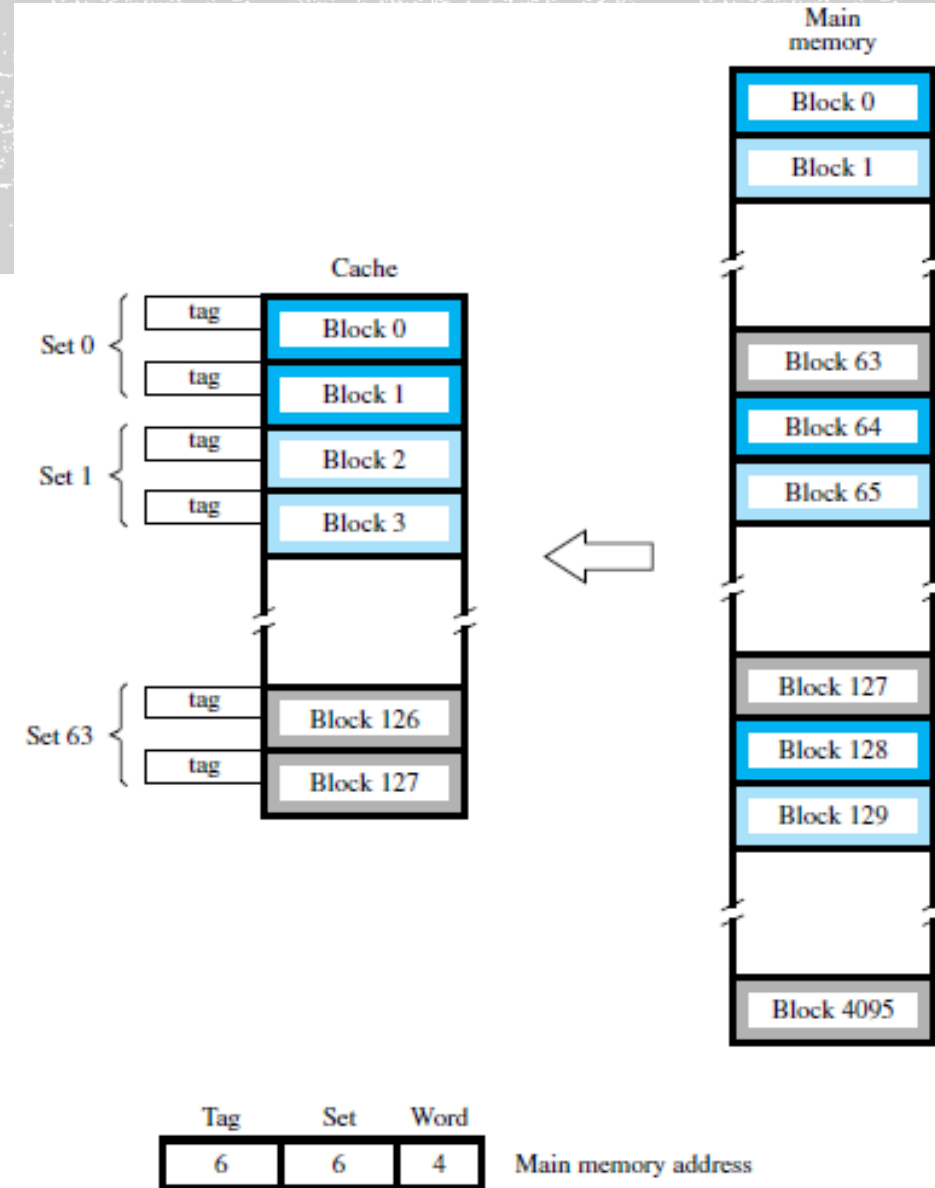


Figure 8.18 Set-associative-mapped cache with two blocks per set.

EXERCISE PROBLEM 1:

- Consider a 2-way set associative mapped cache of size 16 KB with block size 256 bytes. The size of main memory is 128 KB. Find the size of tag, set and word.
- Solution:
 - No. of blocks in the set= 2
 - Size of the cache=16KB
 - No. of blocks in cache= $16\text{KB}/256 = 16384\text{B}/256\text{B} = 64$
 - No. of sets in the cache= $64/2=32=2^5$
 - No. of bits in set field=5
 - No. of words(bytes) in a block= $256=2^8$
 - No. of bits in word field is 8
 - No. of bits in main memory address is 17 bits($\log 128\text{KB}$ to base2)
 - No. of bits in the tag field is 4 ($17-5-8$)

EXERCISE PROBLEM 2:

- A block-set-associative cache consists of a total of 64 blocks, divided into 4-block sets. The main memory contains 4096 blocks, each consisting of 32 words, how many bits are there in each of the Tag, Set, and Word fields?
- Solution:
 - Number of sets = $64/4 = 16$
 - No. of bits in Set field = $4(2^4 = 16)$
 - Word bits = 5 bits ($2^5 = 32$)
 - Tag = $17 - (4 + 5) = 8$

EXERCISE PROBLEM 3:

- A block-set-associative cache consists of a total of 64 blocks, divided into 4-block sets. The main memory contains 4096 blocks, each consisting of 128 words.
 - a) How many bits are there in MM address?
 - b) How many bits are there in each of the TAG, SET & WORD fields
- Solution:
 - Number of sets = $64/4 = 16$
 - Set bits = $4(2^4 = 16)$
 - Number of words = 128
 - Word bits = 7 bits ($2^7 = 128$)
 - MM capacity : 4096×128 ($2^{12} \times 2^7 = 2^{19}$)
 - a) Number of bits in memory address = 19 bits
 - b)

8	4	7
TAG	SET	WORD
 - TAG bits = $19 - (7+4) = 8$ bits.

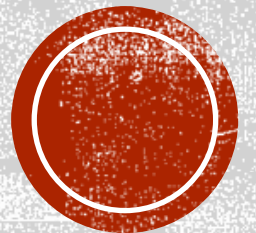
TOPICS COVERED FROM

- Textbook 1:
 - Chapter 8: 8.1, 8.2, 8.2.1, 8.2.5, 8.5, 8.6: 8.6.1

COMPUTER ORGANIZATION AND ARCHITECTURE

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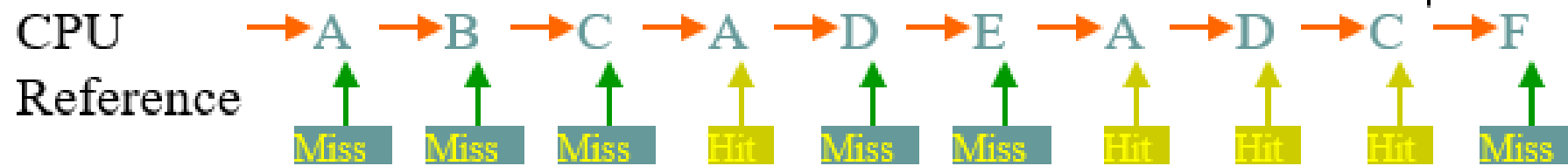
Credits : 04



REPLACEMENT ALGORITHMS

- Difficult to determine which blocks to be removed
- Least Recently Used (LRU) block
- The cache controller tracks references to all blocks as computation proceeds.
- Increase / clear track counters when a hit/miss occurs

REPLACEMENT ALGORITHMS



A	A	A	A	A	A	A	A	A	A
	B	B	B	B	E	E	E	E	F
		C	C	C	C	C	C	C	C
				D	D	D	D	D	D

$$\text{Hit Ratio} = 4 / 10 = 0.4$$

LRU ALGORITHM

- The cache controller must track references to all blocks as computation proceeds.
- Suppose it is required to track the LRU block of a four-block set in a set-associative cache.
- A 2-bit counter can be used for each block.
- When a hit occurs,
 - the counter of the block that is referenced is set to 0.
 - Counters with values originally lower than the referenced one are incremented by one, and
 - all others remain unchanged.
- When a miss occurs and the set is not full,
 - the counter associated with the new block loaded from the main memory is set to 0, and
 - the values of all other counters are increased by one.
- When a miss occurs and the set is full,
 - the block with the counter value 3 is removed,
 - the new block is put in its place, and its counter is set to 0.
 - The other three block counters are incremented by one.
- It can be easily verified that the counter values of occupied blocks are always distinct

LRU ALGORITHM

- Assume counter values as shown

00	Block0
01	Block1
10	Block2
11	Block3

- Suppose hit occurs for block 2

01	Block0
10	Block1
00	Block2
11	Block3

LRU ALGORITHM

- A 4×10 array of numbers, each occupying one word, is stored in main memory locations 7A00 through 7A27 (hex). The elements of this array, A, are stored in column order, as shown below. Assume the data cache has space for only eight blocks of data.

$$A(0, i) \leftarrow \frac{A(0, i)}{\left(\sum_{j=0}^9 A(0, j)\right) / 10} \quad \text{for } i = 0, 1, \dots, 9$$

```
SUM := 0
for j := 0 to 9 do
    SUM := SUM + A(0,j)
end
AVG := SUM/10
for i := 9 downto 0 do
    A(0,i) := A(0,i)/AVG
end
```

Figure 8.20 Task for example in Section 8.6.3.

LRU ALGORITHM

- No. of words in each block = 1 ($2^0=1$)
 - Hence 0 bits to identify words within the block
- Direct mapped:
 - 8 blocks in cache: 3 bits to represent
- Set-associative:
 - 1 bit to identify set 0 or 1
- Associative:
 - All bits are considered tag

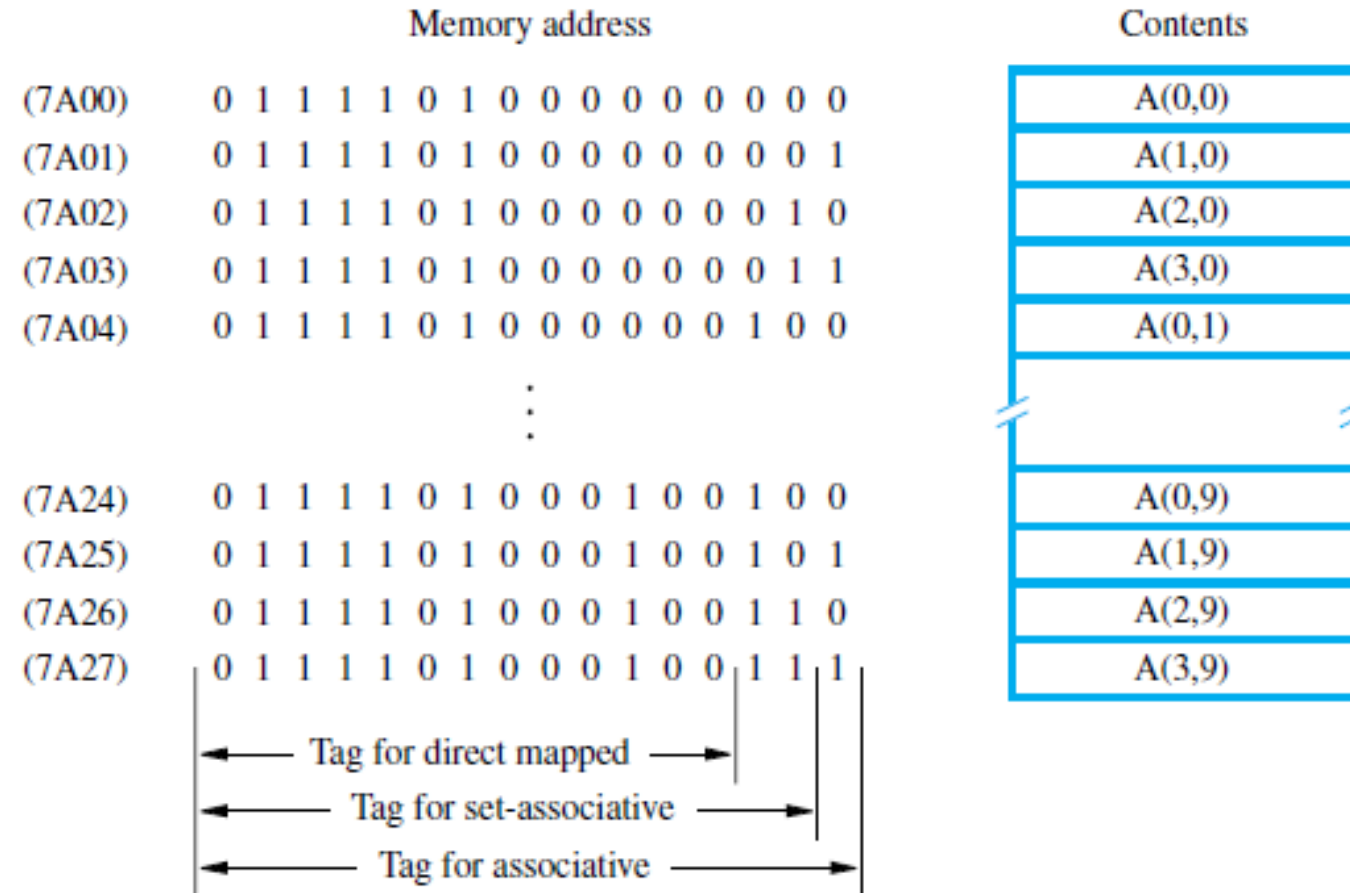


Figure 8.19 An array stored in the main memory.

DIRECT MAPPED CACHE

	Contents of data cache after pass:								
Block position	$j = 1$	$j = 3$	$j = 5$	$j = 7$	$j = 9$	$i = 6$	$i = 4$	$i = 2$	$i = 0$
0	A(0,0)	A(0,2)	A(0,4)	A(0,6)	A(0,8)	A(0,6)	A(0,4)	A(0,2)	A(0,0)
1									
2									
3									
4	A(0,1)	A(0,3)	A(0,5)	A(0,7)	A(0,9)	A(0,7)	A(0,5)	A(0,3)	A(0,1)
5									
6									
7									

Figure 8.21 Contents of a direct-mapped data cache.

ASSOCIATIVE MAPPED CACHE

Block position	Contents of data cache after pass:				
	$j = 7$	$j = 8$	$j = 9$	$i = 1$	$i = 0$
0	A(0,0)	A(0,8)	A(0,8)	A(0,8)	A(0,0)
1	A(0,1)	A(0,1)	A(0,9)	A(0,1)	A(0,1)
2	A(0,2)	A(0,2)	A(0,2)	A(0,2)	A(0,2)
3	A(0,3)	A(0,3)	A(0,3)	A(0,3)	A(0,3)
4	A(0,4)	A(0,4)	A(0,4)	A(0,4)	A(0,4)
5	A(0,5)	A(0,5)	A(0,5)	A(0,5)	A(0,5)
6	A(0,6)	A(0,6)	A(0,6)	A(0,6)	A(0,6)
7	A(0,7)	A(0,7)	A(0,7)	A(0,7)	A(0,7)

Figure 8.22 Contents of an associative-mapped data cache.

SET ASSOCIATIVE MAPPED CACHE

		Contents of data cache after pass:					
		$j = 3$	$j = 7$	$j = 9$	$i = 4$	$i = 2$	$i = 0$
Set 0	{	A(0,0)	A(0,4)	A(0,8)	A(0,4)	A(0,4)	A(0,0)
		A(0,1)	A(0,5)	A(0,9)	A(0,5)	A(0,5)	A(0,1)
		A(0,2)	A(0,6)	A(0,6)	A(0,6)	A(0,2)	A(0,2)
		A(0,3)	A(0,7)	A(0,7)	A(0,7)	A(0,3)	A(0,3)
Set 1	{						

Figure 8.23 Contents of a set-associative-mapped data cache

VIRTUAL MEMORIES

- Physical main memory is not as large as the address space spanned by an address issued by the processor.

$$2^{32} = 4 \text{ GB}, 2^{64} = \dots$$

- When a program does not completely fit into the main memory, the parts of it not currently being executed are stored on secondary storage devices.
- Techniques that automatically move program and data blocks into the physical main memory when they are required for execution are called virtual-memory techniques.
- Virtual addresses will be translated into physical addresses.

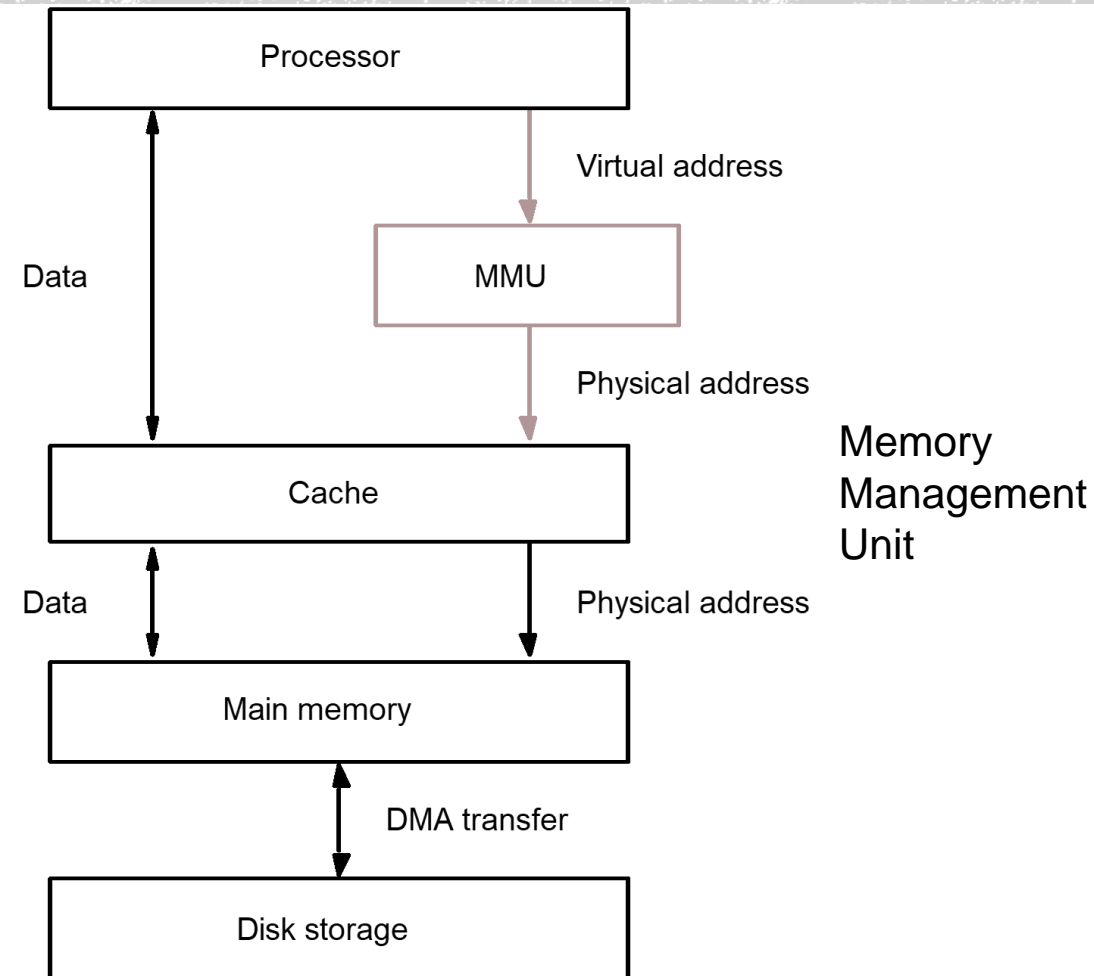


Figure 5.26. Virtual memory organization.

ADDRESS TRANSLATION

- All programs and data are composed of fixed-length units called pages, each of which consists of a block of words that occupy contiguous locations in the main memory.
- Page cannot be too small or too large.
- The virtual memory mechanism bridges the size and speed gaps between the main memory and secondary storage – like cache.
- Information about the main memory location of each page is kept in a page table.
 - includes the main memory address where the page is stored and the current status of the page
 - Validity, modified
- An area in the main memory that can hold one page is called a page frame.
- The starting address of the page table is kept in a page table base register.
- By adding the virtual page number to the contents of this register, the address of the corresponding entry in the page table is obtained.
- The contents of this location give the starting address of the page if that page currently resides in the main memory.

ADDRESS TRANSLATION

- The page table information is used by the MMU for every access, so it is supposed to be with the MMU.
- Since MMU is on the processor chip and the page table is rather large, only small portion of it, which consists of the page table entries that correspond to the most recently accessed pages, can be accommodated within the MMU.
- Translation Lookaside Buffer (TLB)

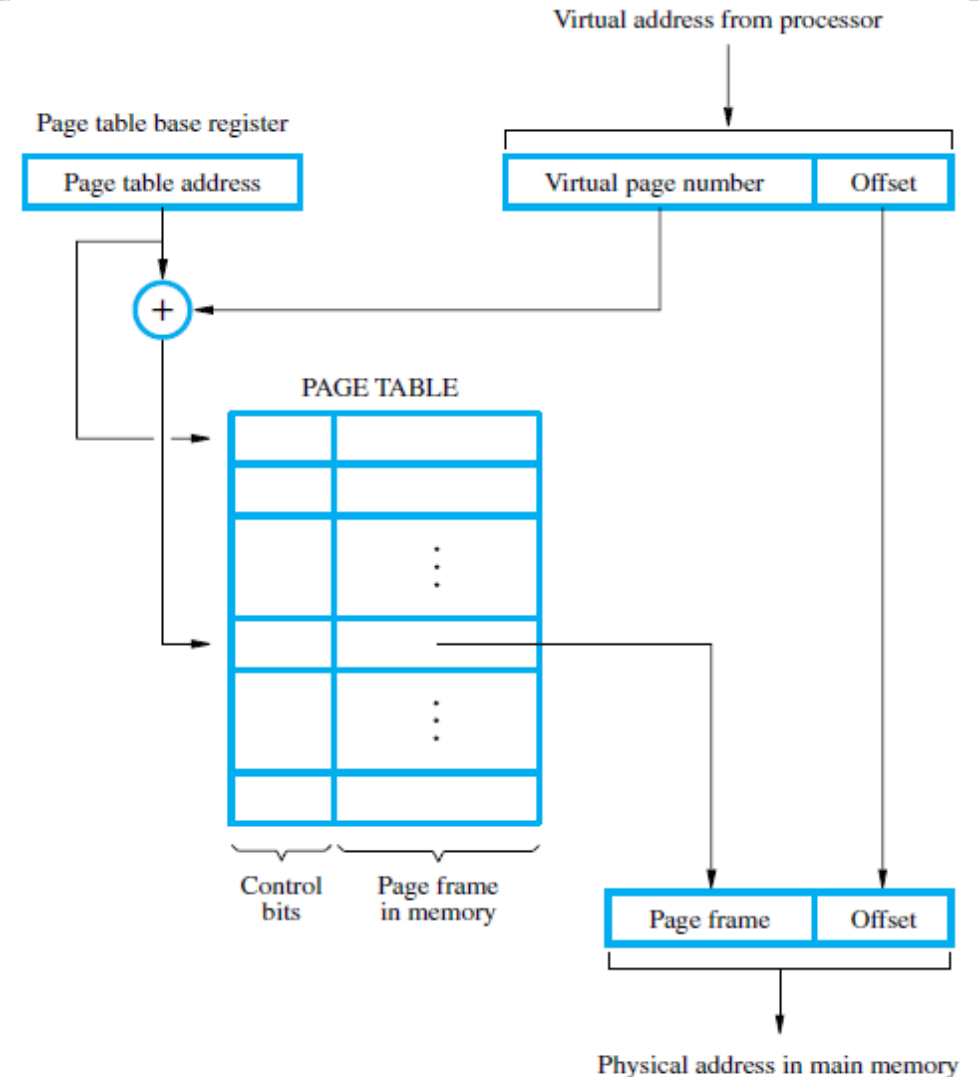


Figure 8.25 Virtual-memory address translation.

TRANSLATION PROCEDURE

- Given a virtual address, the MMU looks in the TLB for the referenced page. If the page table entry for this page is found in the TLB, the physical address is obtained immediately. If there is a miss in the TLB, then the required entry is obtained from the page table in the main memory and the TLB is updated.
- The contents of TLB must be coherent with the contents of page tables in the memory
- When the operating system changes the contents of a page table, it must simultaneously invalidate the corresponding entries in the TLB. One of the control bits in the TLB is provided for this purpose. When an entry is invalidated, the TLB acquires the new information from the page table in the memory as part of the MMU's normal response to access misses.
- Write-through is not suitable for virtual memory.
- Locality of reference in virtual memory

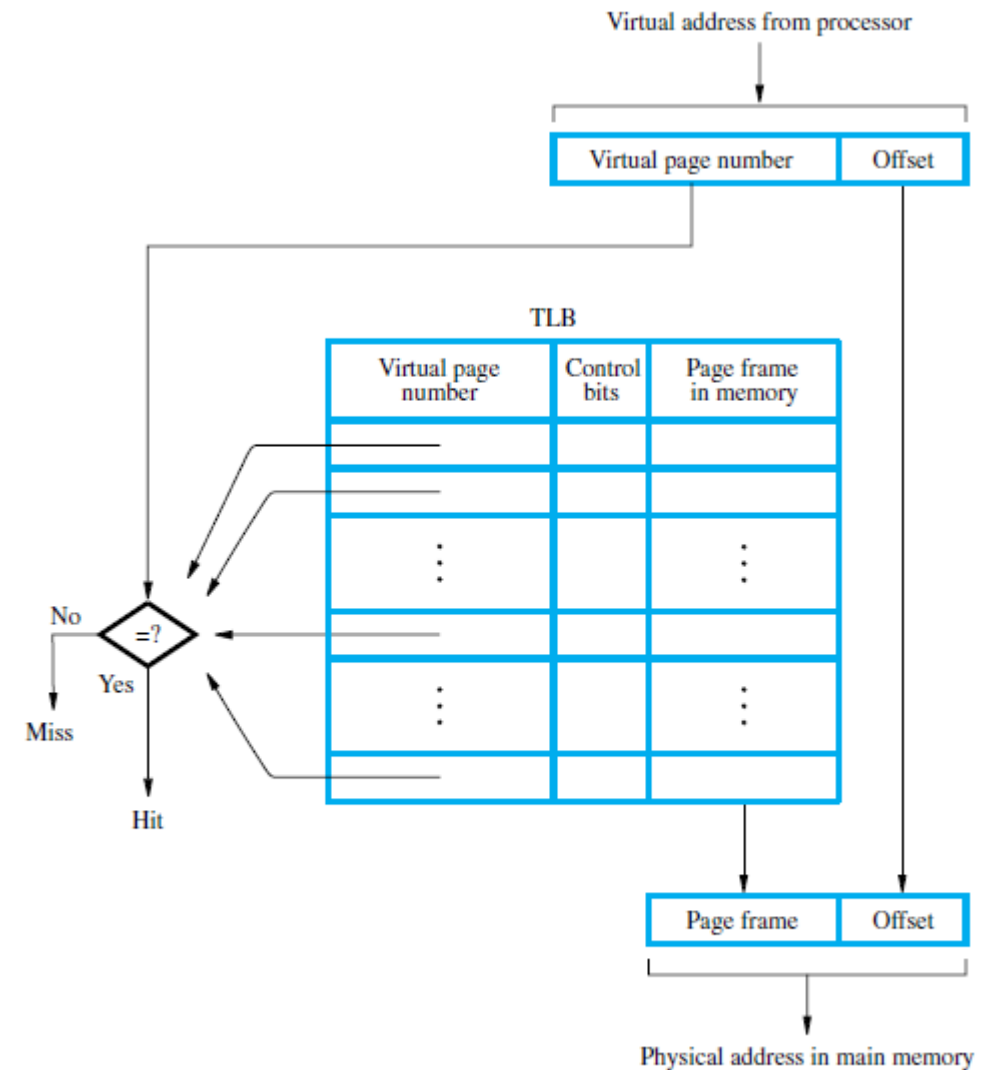


Figure 8.26 Use of an associative-mapped TLB.

PAGE FAULT AND PAGE REPLACEMENT

- When a program generates an access request to a page that is not in the main memory, a page fault is said to have occurred.
- The entire page must be brought from the disk into the memory before access can proceed. When it detects a page fault, the MMU asks the operating system to intervene by raising an exception (interrupt).
- Page Replacement:
 - If a new page is brought from the disk when the main memory is full, it must replace one of the resident pages.
 - The problem of choosing which page to remove is just as critical here as it is in a cache, and the observation that programs spend most of their time in a few localized areas also applies.
 - Concepts similar to the LRU replacement algorithm can be applied to page replacement, and the control bits in the page table entries can be used to record usage history
 - A modified page has to be written back to the disk before it is removed from the main memory. It is important to note that the write-through protocol, which is useful in the framework of cache memories, is not suitable for virtual memory. The access time of the disk is so long that it does not make sense to access it frequently to write small amounts of data

EXERCISE PROBLEM

- A byte-addressable computer has a small data cache capable of holding eight 32-bit words. Each cache block consists of one 32-bit word. When a given program is executed, the processor reads data sequentially from the following hex addresses:

200, 204, 208, 20C, 2F4, 2F0, 200, 204, 218, 21C, 24C, 2F4

This pattern is repeated four times.

- a) Assume that the cache is initially empty. Show the contents of the cache at the end of each pass through the loop if a direct-mapped cache is used and compute the hit rate.
- b) Repeat part a) for an associative-mapped cache that uses the LRU replacement algorithm.
- c) Repeat part (a) for a four-way set-associative cache.

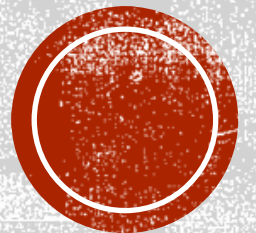
TOPICS COVERED FROM

- Textbook 1:
 - Chapter 8: 8.6.2, 8.6.3, 8.8

COMPUTER ORGANIZATION AND ARCHITECTURE

Course Code : CSE 2151

Credits : 04



PERFORMANCE CONSIDERATIONS

- Hit Rate and Miss Penalty
- Caches on the Processor Chip
- Other Enhancements

HIT RATE AND MISS PENALTY

- Hit rate:
 - number of hits stated as a fraction of all attempted accesses
- Miss rate:
 - number of misses stated as a fraction of attempted accesses
- The entire memory hierarchy would appear to the processor as a single memory unit that has the access time of the cache on the processor chip and the size of the magnetic disk
- The total access time seen by the processor when a miss occurs -miss penalty

- System with only one level of cache
 - the time to access a block of data in the main memory.
- Let h be the hit rate, M the miss penalty, and C the time to access information in the cache
- The average access time experienced by the processor is
- $t_{\text{avg}} = hC + (1 - h)M$

EXAMPLE

- Consider a computer that has the following parameters. Access times to the cache and the main memory are τ and 10τ , respectively. When a cache miss occurs, a block of 8 words is transferred from the main memory to the cache. It takes 10τ to transfer the first word of the block, and the remaining 7 words are transferred at the rate of one word every τ seconds.
- Miss penalty in this computer is given by:
$$M = \tau + 10\tau + 7\tau + \tau = 19\tau$$

EXAMPLE

- Assume that 30 percent of the instructions in a typical program perform a Read or a Write operation, which means that there are 130 memory accesses for every 100 instructions executed. Assume that the hit rates in the cache are 0.95 for instructions and 0.9 for data. Assume further that the miss penalty is the same for both read and write accesses

$$\frac{\text{Time without cache}}{\text{Time with cache}} = \frac{130 \times 10\tau}{100(0.95\tau + 0.05 \times 19\tau) + 30(0.9\tau + 0.1 \times 19\tau)} = 4.7$$

- cache makes the memory appear almost five times faster than it really is
- Let us consider how effective the cache of this example is compared to the ideal case in which the hit rate is 100 percent. 100% hit rate in the cache would make the memory appear twice as fast as when realistic hit rates are used.

$$\frac{\text{Time for real cache}}{\text{Time for ideal cache}} = \frac{100(0.95\tau + 0.05 \times 19\tau) + 30(0.9\tau + 0.1 \times 19\tau)}{130\tau} = 2.1$$

HOW CAN THE HIT RATE BE IMPROVED?

- Make the cache larger
 - increased cost
- increase the cache block size while keeping the total cache size constant, to take advantage of spatial locality
 - the performance of a computer is affected positively by increased hit rate and negatively by increased miss penalty
 - block size should be neither too small nor too large.
 - In practice, block sizes in the range of 16 to 128 bytes are the most popular choices
- miss penalty can be reduced if the load-through approach is used when loading new blocks into the cache.

CACHES ON THE PROCESSOR CHIP

- Most processor chips include at least one L1 cache. Often there are two separate L1 caches, one for instructions and another for data.
- In high-performance processors, two levels of caches are normally used, often implemented on the processor chip.
 - separate L1 caches for instructions and data –fast-10's of KB
 - a larger L2 cache-slower but larger than L1- only affects the miss penalty of the L1 caches-100s of KB or MB
- The average access time experienced by the processor in such a system is:

$$t_{avg} = h_1 C_1 + (1 - h_1)(h_2 C_2 + (1 - h_2)M)$$

where

h_1 is the hit rate in the L1 caches.

h_2 is the hit rate in the L2 cache.

C_1 is the time to access information in the L1 caches.

C_2 is the miss penalty to transfer information from the L2 cache to an L1 cache.

M is the miss penalty to transfer information from the main memory to the L2 cache.

EXERCISE PROBLEM

- Suppose that a computer has a processor with two L1 caches, one for instructions and one for data, and an L2 cache. Let τ be the access time for the two L1 caches. The miss penalties are approximately 15τ for transferring a block from L2 to L1, and 100τ for transferring a block from the main memory to L2. Assume that the hit rates are the same for instructions and data and that the hit rates in the L1 and L2 caches are 0.96 and 0.80, respectively.
 - a. What fraction of accesses miss in both the L1 and L2 caches, thus requiring access to the main memory?
 - b. What is the average access time as seen by the processor?
 - c. Suppose that the L2 cache has an ideal hit rate of 1. By what factor would this reduce the average memory access time as seen by the processor?
 - d. Consider the following change to the memory hierarchy. The L2 cache is removed and the size of the L1 caches is increased so that their miss rate is cut in half. What is the average memory access time as seen by the processor in this case?

EXERCISE PROBLEM: SOLUTION

(a) The fraction of memory accesses that miss in both the L1 and L2 caches is

$$(1 - h_1)(1 - h_2) = (1 - 0.96)(1 - 0.80) = 0.008$$

(b) The average memory access time using two cache levels is

$$\begin{aligned} t_{avg} &= 0.96\tau + 0.04(0.80 \times 15\tau + 0.20 \times 100\tau) \\ &= 2.24\tau \end{aligned}$$

(c) With no misses in the L2 cache, we get:

$$t_{avg}(\text{ideal}) = 0.96\tau + 0.04 \times 15\tau = 1.56\tau$$

Therefore,

$$\frac{t_{avg}(\text{actual})}{t_{avg}(\text{ideal})} = \frac{2.24\tau}{1.56\tau} = 1.44$$

(d) With larger L1 caches and the L2 cache removed, the access time is

$$t_{avg} = 0.98\tau + 0.02 \times 100\tau = 2.98\tau$$

OTHER ENHANCEMENTS: WRITE BUFFER

- Write-through protocol
 - Each Write operation results in writing a new value into the main memory.
 - If the processor must wait for the memory function to be completed, processor is slowed down by all Write requests.
 - Processor does not need immediate access to the result of a Write operation; not necessary for it to wait for the Write request to be completed. Write buffer included for temporary storage of Write requests.
 - Processor places each Write request into this buffer and continues execution of the next instruction.
 - The information from the buffer is sent to the main memory whenever the memory is not responding to Read requests.
 - Read requests be serviced quickly, because the processor usually cannot proceed before receiving the data being read from the memory. These requests are given priority over Write requests
 - The Write buffer may hold several Write requests.
 - subsequent Read request may refer to data that are still in the Write buffer.
 - To ensure correct operation, the addresses of data to be read from the memory are always compared with the addresses of the data in the Write buffer.
 - In the case of a match, the data in the Write buffer are used.

OTHER ENHANCEMENTS: WRITE BUFFER

- Write-back protocol
 - Write commands issued by the processor are performed on the word in the cache.
 - When a new block of data is to be brought into the cache as a result of a Read miss, it may replace an existing block that has some dirty data.
 - The dirty block must be written into the main memory.
 - If the required write-back is performed first, then the processor must wait for this operation to be completed before the new block is read into the cache.
 - It is more prudent to read the new block first.
 - The dirty block being ejected from the cache is temporarily stored in the Write buffer and held there while the new block is being read.
 - Afterwards, the contents of the buffer are written into the main memory.
 - Write buffer also works well for the write-back protocol.

OTHER ENHANCEMENTS: PREFETCHING

- new data are brought into the cache when they are first needed.
- Following a Read miss, the processor has to pause until the new data arrive, thus incurring a miss penalty.
- To avoid stalling the processor, it is possible to prefetch the data into the cache before they are needed
- Through
 - software -prefetch instruction
 - hardware- using circuitry that attempts to discover a pattern in memory references and prefetches data according to this pattern
- Prefetch-Executing this instruction causes the addressed data to be loaded into the cache, as in the case of a Read miss.
- The hope is that prefetching will take place while the processor is busy executing instructions that do not result in a Read miss, thus allowing accesses to the main memory to be overlapped with computation in the processor
- Inserted either by programmer or compiler
- Overhead
 - Increases length of program
 - Data may not be used by instructions that follow-if the prefetched data are ejected from the cache by a Read miss involving other data

OTHER ENHANCEMENTS: LOCKUP-FREE CACHE

- Software prefetching does not work well if the action of prefetching stops other accesses to the cache until the prefetch is completed
- While servicing a miss, the cache is said to be locked.
- modify the basic cache structure to allow the processor to access the cache while a miss is being serviced
- A cache that can support multiple outstanding misses is called lockup-free.
- cache must include circuitry that keeps track of all outstanding misses

TOPICS COVERED FROM

- Textbook 1:
 - Chapter 8: 8.7

COMPUTER ORGANIZATION AND ARCHITECTURE

Course Code : CSE 2151

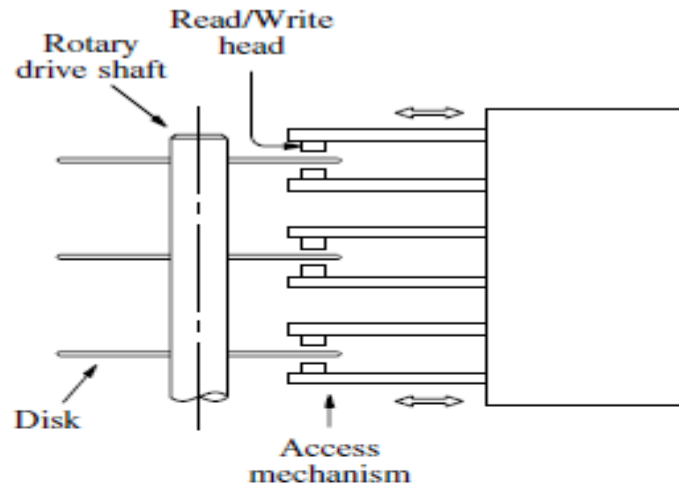
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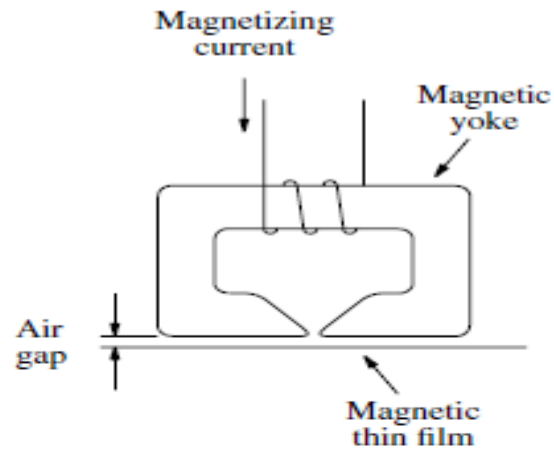
SECONDARY STORAGE: MAGNETIC HARD DISKS

- One or more disk platters mounted on a common spindle.
- A thin magnetic film is deposited on each platter, usually on both sides.
- The assembly is placed in a drive that causes it to rotate at a constant speed.
- The magnetized surfaces move in close proximity to read/write heads
- Data are stored on concentric tracks
- Read/write heads move radially to access different tracks

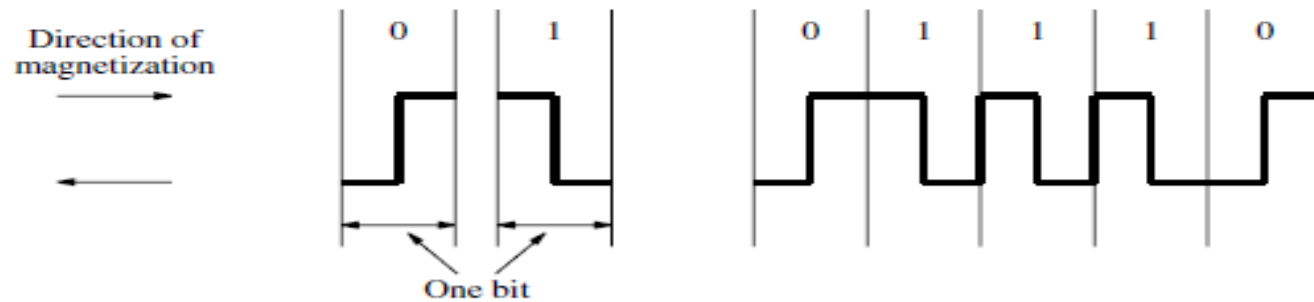
SECONDARY STORAGE: MAGNETIC HARD DISKS



(a) Mechanical structure



(b) Read/Write head detail



(c) Bit representation by phase encoding

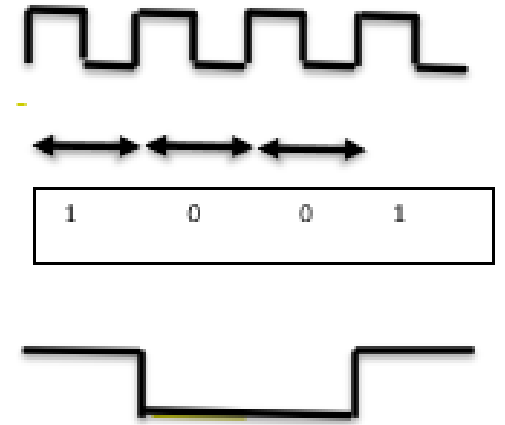


Figure 8.27 Magnetic disk principles.

READ WRITE HEAD

- Each read/write head consists of a magnetic yoke and a magnetizing coil.
- Digital information can be stored on the magnetic film by applying current pulses of suitable polarity to the magnetizing coil.
- This causes the magnetization of the film in the area immediately underneath the head to switch to a direction parallel to the applied field.
- The same head can be used for reading the stored information.
- Changes in the magnetic field in the vicinity of the head caused by the movement of the film relative to the yoke induce a voltage in the coil, which now serves as a sense coil.
- The polarity of this voltage is monitored by the control circuitry to determine the state of magnetization of the film.
- if the binary states 0 and 1 are represented by two opposite states of magnetization, a voltage is induced in the head only at 0-to-1 and at 1-to-0 transitions in the bit stream.
- A long string of 0s or 1s causes an induced voltage only at the beginning and end of the string.

PHASE ENCODING OR MANCHESTER ENCODING

- changes in magnetization occur for each data bit
- Clocking information is provided by the change in magnetization at the midpoint of each bit period.
- The drawback of Manchester encoding is its poor bit-storage density
- disks and the read/write heads are placed in a sealed, air-filtered enclosure.
- known as *Winchester technology*

MAGNETIC HARD DISK

- The disk system consists of three key parts.
- the assembly of disk platters- usually referred to as the disk.
- The Electromechanical mechanism that spins the disk and moves the read/write heads -called the disk drive
- the disk controller, which is the electronic circuitry that controls the operation of the system - may be implemented as a separate module, or it may be incorporated into the enclosure that contains the entire disk system

ORGANIZATION OF DATA ON A DISK

- Each surface is divided into concentric tracks, and each track is divided into sectors.
- The set of corresponding tracks on all surfaces of a stack of disks forms a logical cylinder
- All tracks of a cylinder can be accessed without moving the read/write heads.
- Data are accessed by specifying the surface number, the track number, and the sector number.
- Read and Write operations always start at sector boundaries.

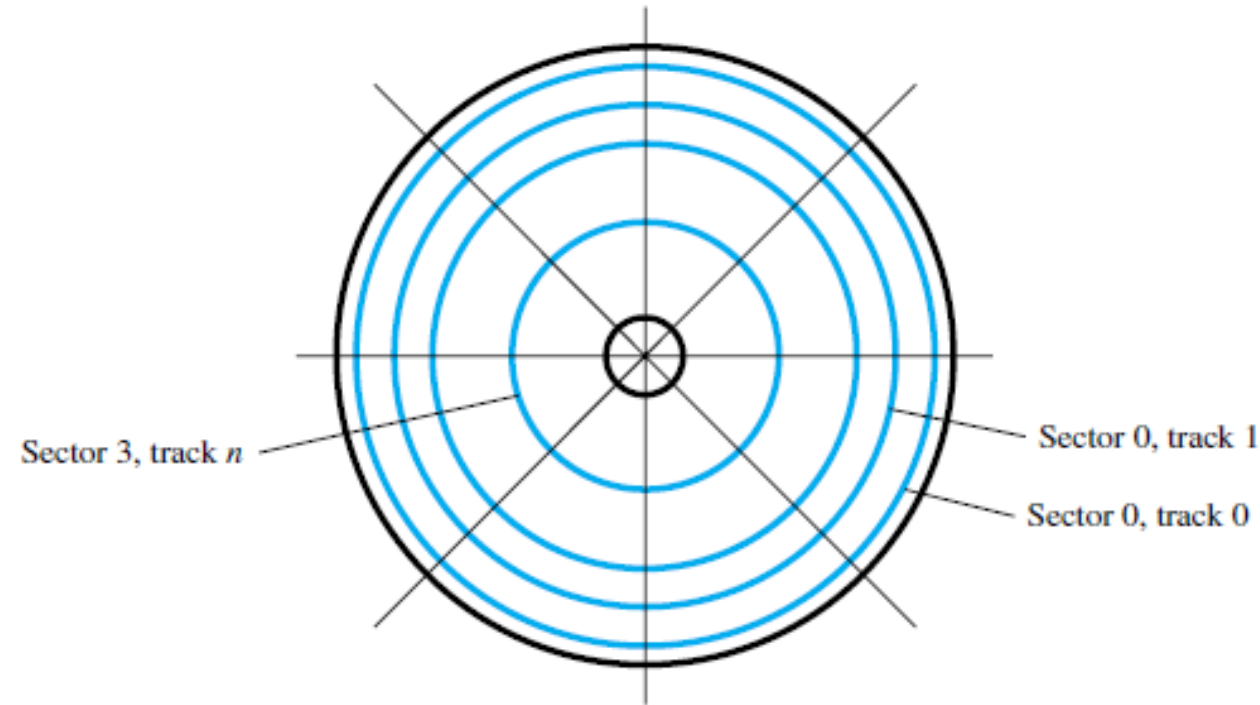


Figure 8.28 Organization of one surface of a disk.

ACCESS DATA ON A DISK

- Data bits are stored serially on each track
- Each sector may contain 512 or more bytes.
- Sector header-contains identification (addressing) information used to find the desired sector on the selected track
- Following the data, there is an error-correction code (ECC)-used to detect and correct errors that may have occurred in writing or reading the data bytes
- small inter-sector gap that enables the disk control circuitry to distinguish easily between two consecutive sectors.
- An unformatted disk has no information on its tracks.
- Formatting process writes markers that divide the disk into tracks and sectors. During this process, the disk controller may discover some sectors or even whole tracks that are defective. The disk controller keeps a record of such defects and excludes them from use.
- The formatting information comprises sector headers, ECC bits, and inter-sector gaps.
- The capacity of a formatted disk, after accounting for the formatting information overhead, is the proper indicator of the disk's storage capability.
- After formatting, the disk is divided into logical partitions

ACCESS DATA ON A DISK

- Each track has the same number of sectors, which means that all tracks have the same storage capacity.
- The stored information is packed more densely on inner tracks than on outer tracks
- also possible to increase the storage density by placing more sectors on the outer tracks, which have longer circumference
- Requires more complicated access circuitry.
- Access time
 - seek time -time required to move the read/write head to the proper track
 - rotational delay (latency)-time taken to reach the addressed sector after the read/write head is positioned over the correct track.

DATA BUFFER/CACHE

- Data buffer/cache -disk drive is connected to the rest of a computer system using some standard interconnection scheme, such as SCSI (Small Computer System Interface) or SATA (Serial Advanced Technology Attachment) usually capable of transferring data at much higher rates than the rate at which data can be read from disk tracks.
- Include a data buffer in the disk unit-to deal with difference in speed
- The buffer is a semiconductor memory, capable of storing a few megabytes of data. The requested data are transferred between the disk tracks and the buffer at a rate dependent on the rotational speed of the disk.
- Transfers between the data buffer and the main memory can then take place at the maximum rate allowed by the interconnect between them.

DISK CONTROLLER

- Operation of a disk drive is controlled by a disk controller circuit, which also provides an interface between the disk drive and the rest of the computer system.
- One disk controller may be used to control more than one drive.
- A disk controller that communicates directly with the processor contains a number of registers that can be read and written by the operating system.
- communication between the OS and the disk controller is achieved in the same manner as with any I/O interface
- The OS initiates the transfers by issuing Read and Write requests, which entail loading the controller's registers with the necessary addressing and control information.
- Typically, this information includes:
 - Main memory address—The address of the first main memory location of the block of words involved in the transfer.
 - Disk address—The location of the sector containing the beginning of the desired block of words.
 - Word count—The number of words in the block to be transferred.

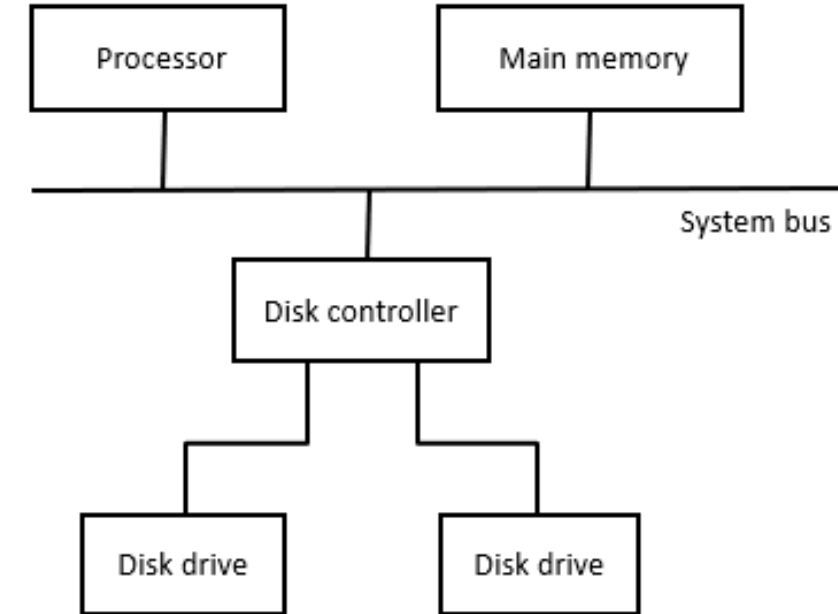


Figure 5.31. Disks connected to the system bus.

DISC CONTROLLER FUNCTIONS

- On the disk drive side, the controller's major functions are:
- Seek-Causes the disk drive to move the read/write head from its current position to the desired track.
- Read-Initiates a Read operation, starting at the address specified in the disk address register.
- Write-Transfers data to the disk
- Error checking-Computes the error correcting code (ECC) value for the data read from a given sector and compares it with the corresponding ECC value read from the disk

EXERCISE PROBLEM

- Consider a long sequence of accesses to a disk with an average seek time of 6 ms and an average rotational delay of 3 ms. The average size of a block being accessed is 8K bytes. The data transfer rate from the disk is 34 Mbytes/sec.
 - a) Assuming that the data blocks are randomly located on the disk, estimate the average percentage of the total time occupied by seek operations and rotational delays.
 - b) Repeat part (a) for the situation in which disk accesses are arranged so that in 90 percent of the cases, the next access will be to a data block on the same cylinder.
- Solution:
 - It takes $8K/34M = 0.23$ ms to transfer a block of data.
 - a. The total time needed to access each block is $6 + 3 + 0.23 = 9.23$ ms. The portion of time occupied by seek and rotational delay is $9/9.23 = 0.97 = 97\%$.
 - b. In 90% of the cases, only rotational delays are involved. Therefore, the average time to access a block is $0.9 \times 3 + 0.1 \times 9 + 0.23 = 3.89$ ms.
The portion of time occupied by seek and rotational delay is $3.6/3.89 = 0.92 = 92\%$.

EXERCISE PROBLEM

- A disk unit has 24 recording surfaces. It has a total of 14,000 cylinders. There is an average of 400 sectors per track. Each sector contains 512 bytes of data.
- (a) What is the maximum number of bytes that can be stored in this unit?
- (b) What is the data transfer rate in bytes per second at a rotational speed of 7200 rpm?
- Solution
- (a) The maximum number of bytes that can be stored on this disk is $24 \times 14000 \times 400 \times 512 = 68.8 \times 10^9$ bytes.
- (b) The data transfer rate is $(400 \times 512 \times 7200)/60 = 24.58 \times 10^6$ bytes/s.

TOPICS COVERED FROM

- Textbook 1:
 - Chapter 8: 8.8, 8.10, 8.10.1