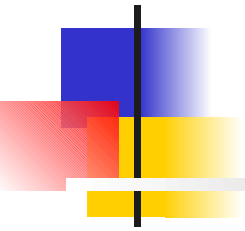
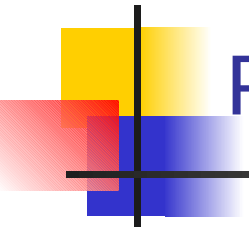
Chapter 12

# Paging an Virtual Memory Systems





# Paging & Virtual Memory

1. **Virtual Memory** − giving the illusion of more physical memory than there really is (via demand paging)
2. **Pure Paging** − The total program is kept in memory as sets of (non−contiguous) pages
    1. No illusion of virtual memory
3. **Demand Paging** − A program's "working set" is kept in memory, reference outside WS causes corrsponding code to be retrieved from disk ("page fault")
    - Provides the illusion of virtual memory

# Paging Systems

1. Processes (programs) are divided into fixed size pieces called **Pages**
2. Main memory is divided into fixed size partitions called **Blocks** (**Page Frames)**
3. **Pure Paging** − entire program is kept in memory during execution, but pages are not kept in contiguous blocks
4. **Demand paging –** only parts of program kept in memory during execution, pages are not kept in contiguous blocks

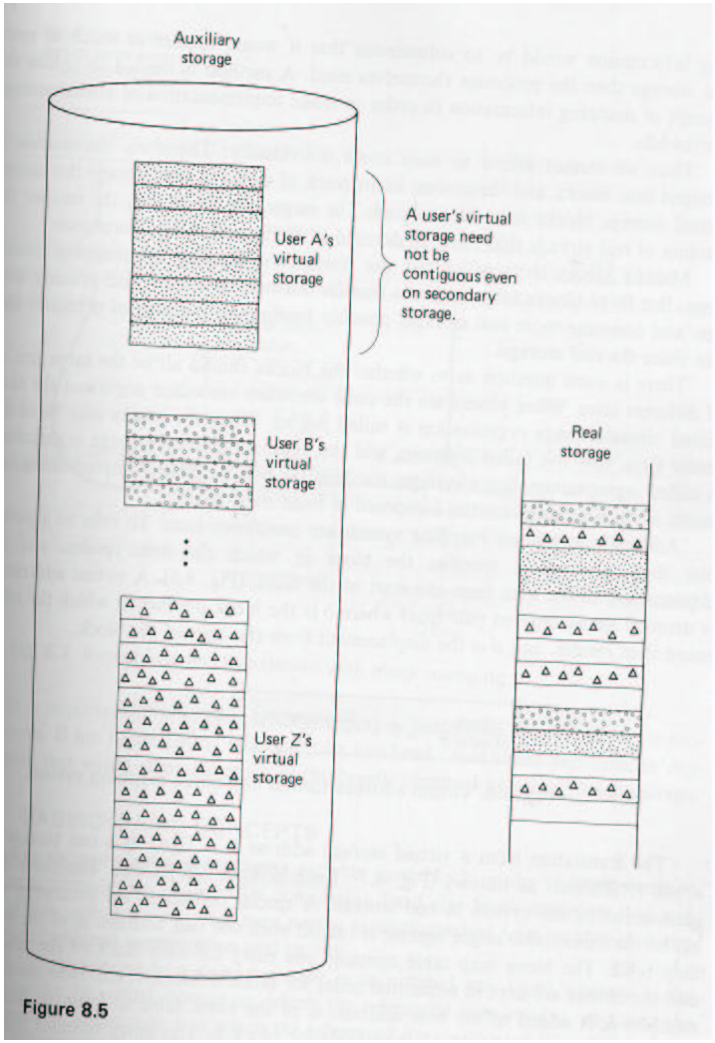


Figure 8.5

# Virtual Versus Physical Addresses

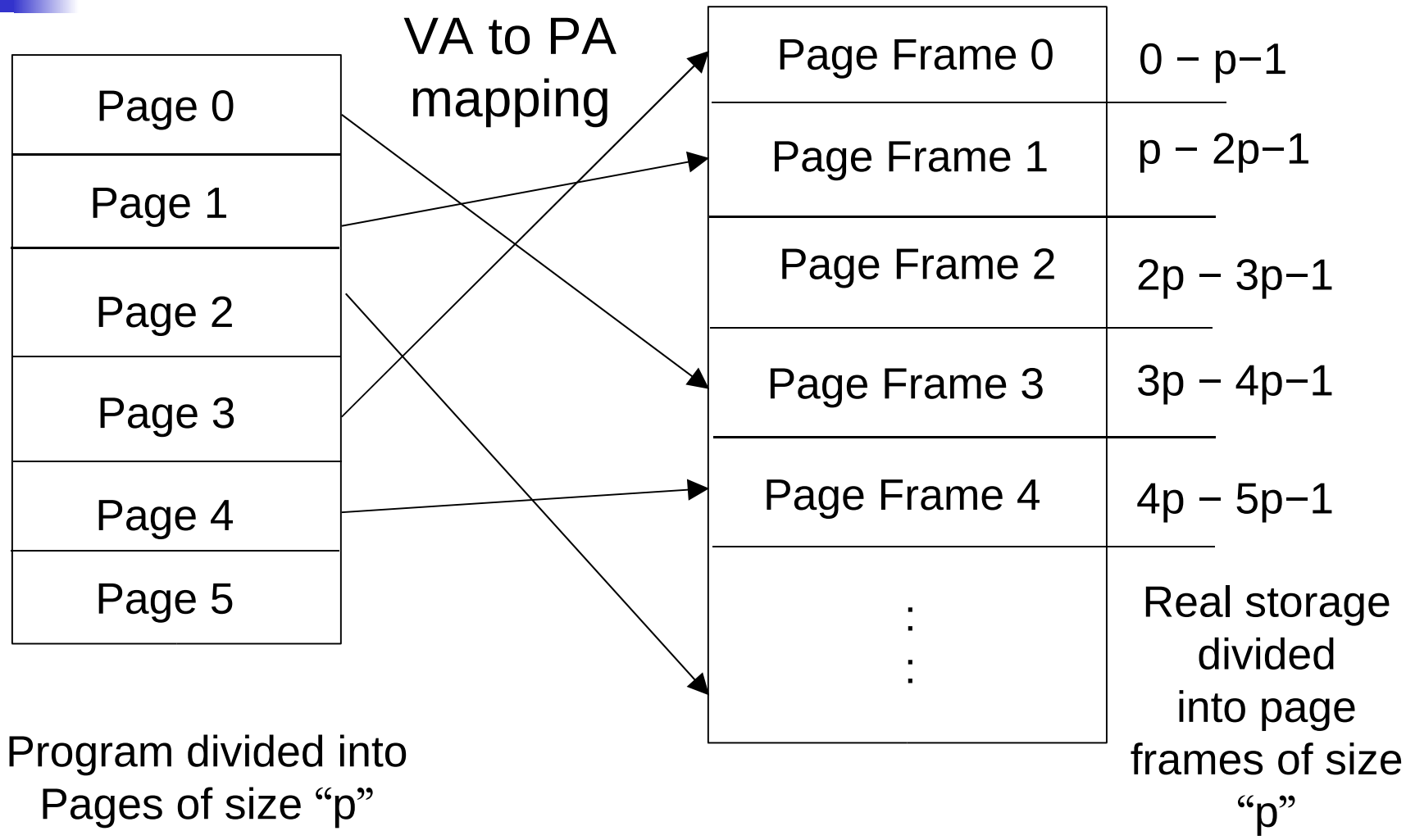
1. A *virtual address* is represented as <page, offset> where the page is determined by dividing each process into fixed size *pages,* the offset is a number in the range 0 − (page_size−1) .
2. Memory is divided into fixed size *blocks* (or *page frames*) and accommodates a process' pages. The physical address (PA) then is (block_number * page_size + offset).
3. In pure paging systems the entire VA space of a process must reside in physical memory during execution, but pages are *not* kept in contiguous blocks.

# Pure Paging Virtual Addresses…

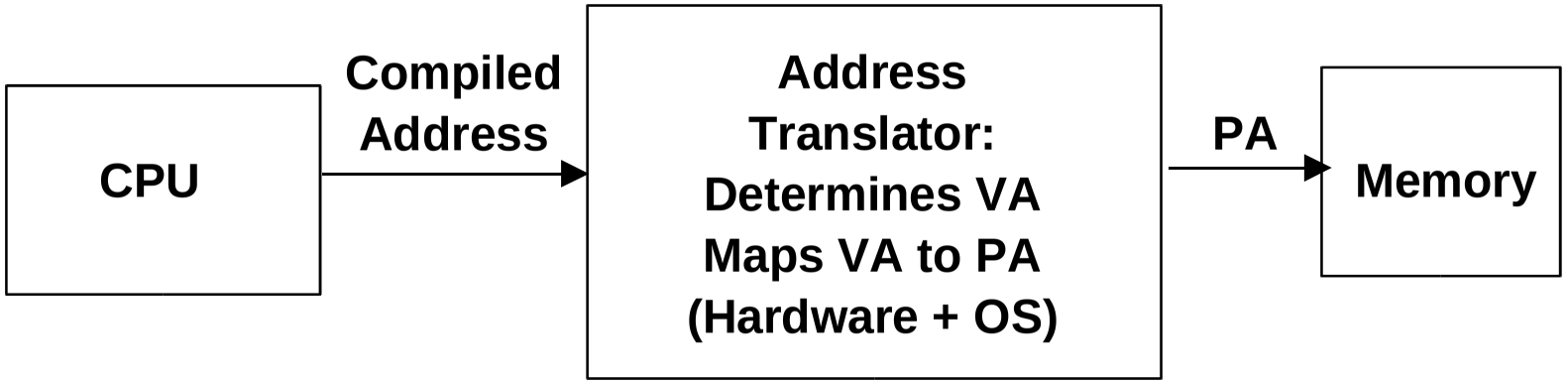
1. VA is determined from the compiled address
2. VA has two components:

| page number | address in page (or offset or displacement) |
|---|---|

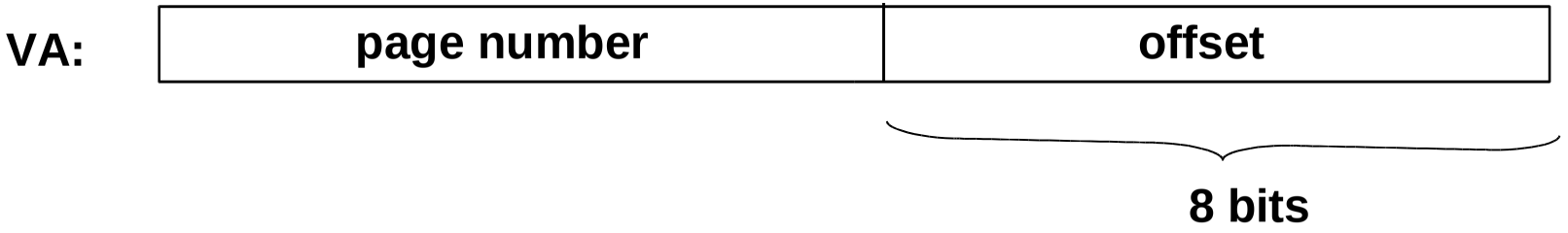
# Virtual Address to Physical Address Mapping



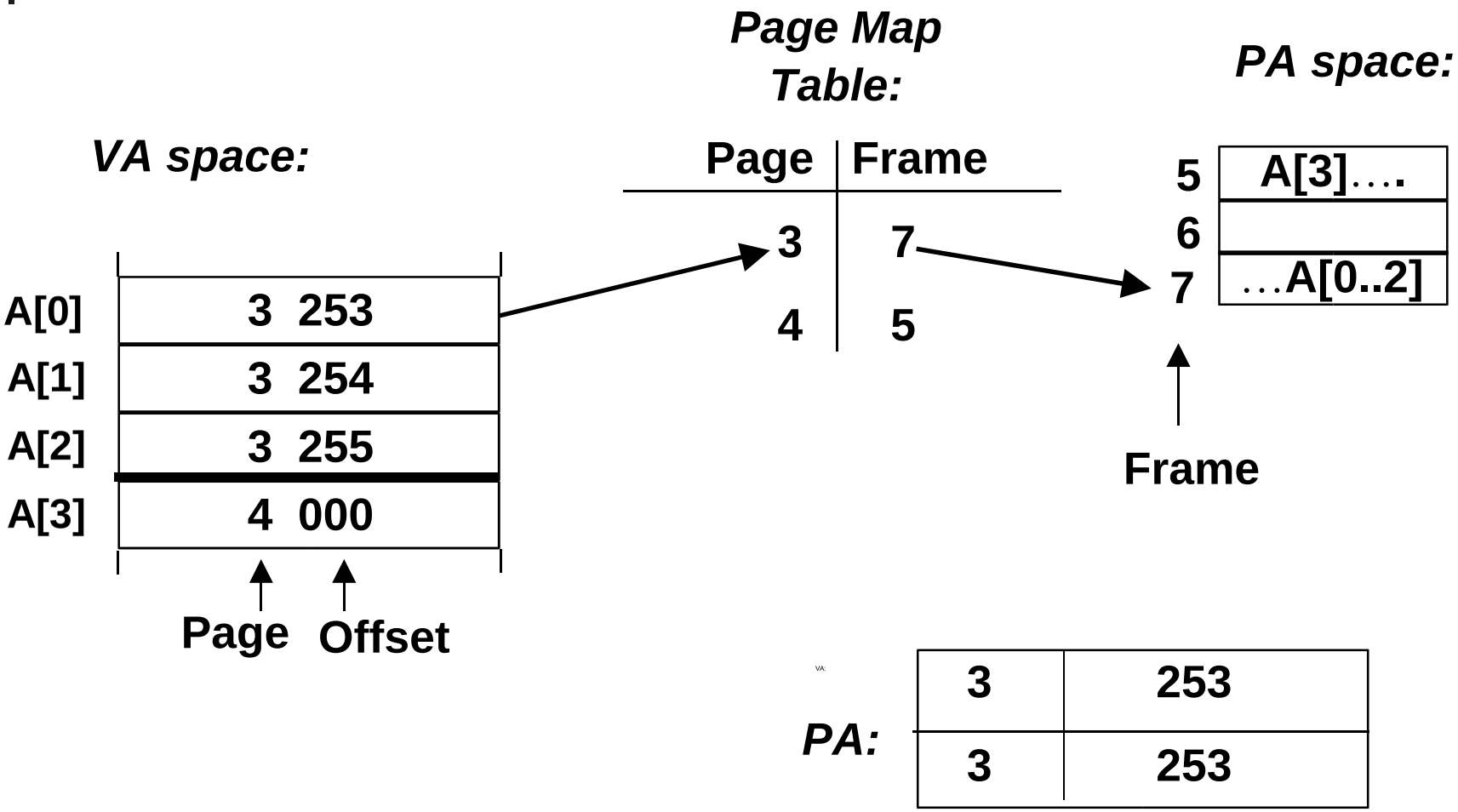
# Key Idea in Paging Systems




**Assume 256 bytes per page:**

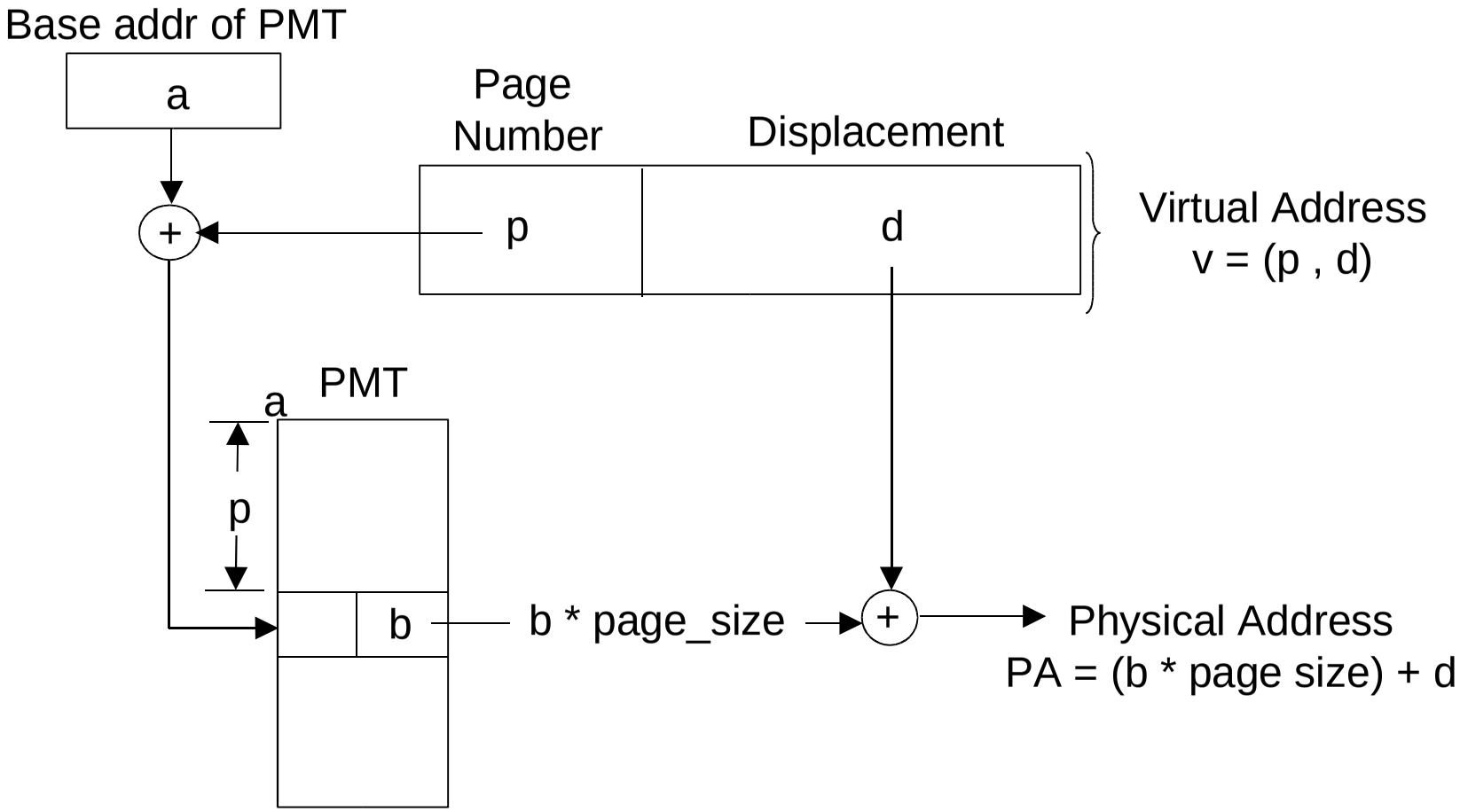


# Key Idea in Paging Systems…

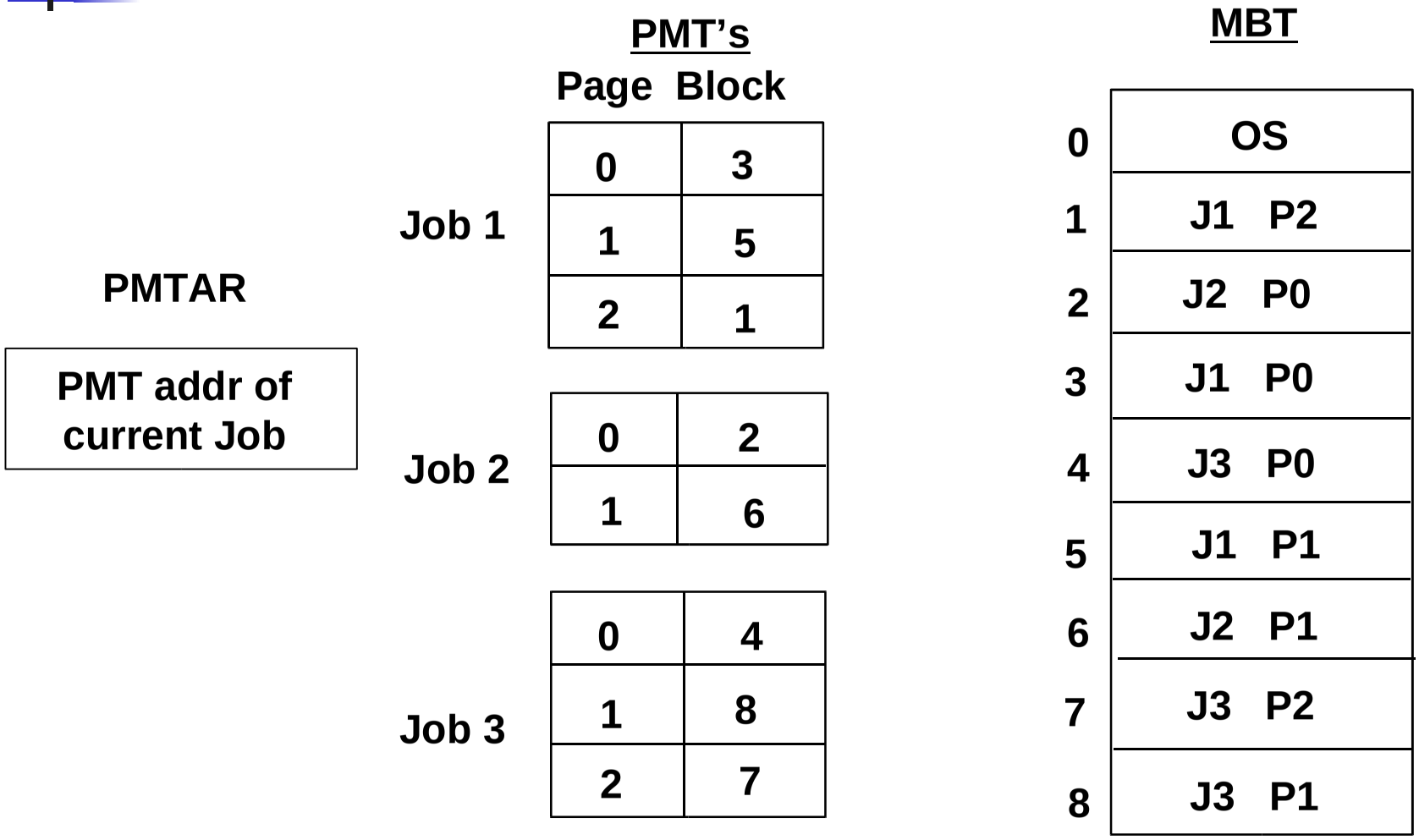



| | | |
|---|---|---|
| VA: | 3 | 253 |
| PA: | 3 | 253 |

# Addressing Scheme



# Paging Mapping Example



# Page Management

***Page Map Table (PMT):***

Contains VA page to PA block mapping

| Page | Block |
|---|---|
| 0 | 7 |
| 1 | 2 |
| 2 | 13 |

1 PMT / job

1 Entry / page

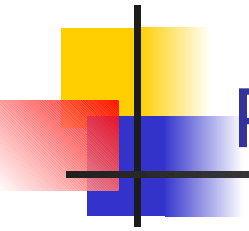
# Page Management

***Page Map Table Address Register (PMTAR):***

| Length of program in pages (# PMT entries) | Base address of current PMT |
|---|---|

Points to PMT for currently executing job

1 PMTAR / System



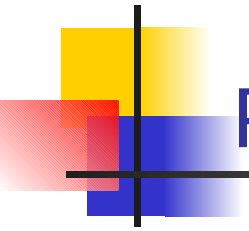
# Page Management …

**Memory Block Table (MBT)**

Maps each block of main memory either to a process id and page number or to "free"

1 MBT / System

1 Entry / Block



# Page Management …

**Process (Job) Control Block (PCB)**

Contains information about all jobs in the system

Stores: Job Size

Location of PMT

1 PCB / system

1 entry / job

# Page Addressing − Let's get REAL

VA = < page, offset >

PA = block size * block + offset

Assume:

1 w**ord** PMT entries;

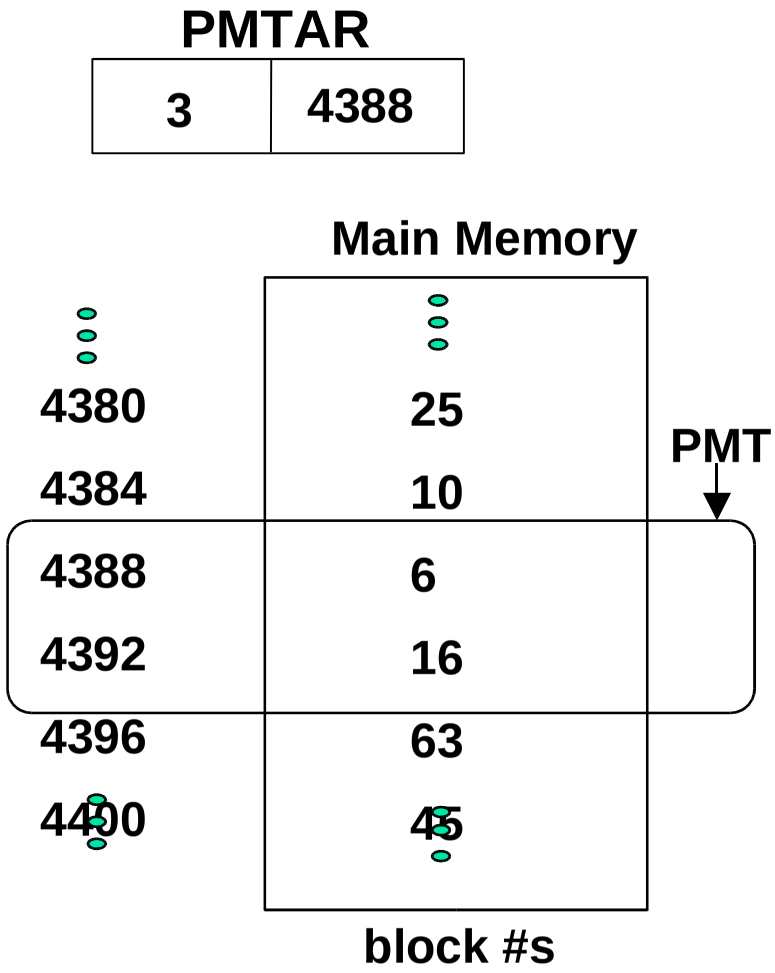
b**yte** addressable MM

*Example:*

page & block size = 4 K **bytes**

VA = < 1, 1234 >

PA = 4096 * 16 + 1234



# Determining Virtual Address <Page , Offset> from the Compiled Address

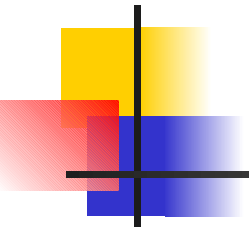
Compiled Address (relative to 0) : 18087

Page size: 2K (2048 **bytes**)
Memory is **byte** addressable

Virtual Address:
Page = Div (Compiled Address, Page Size)
Offset = MOD (Compiled Address, Page Size)

<8 , 1703>

DIV => “Shift right”, 11 bits ($2048 = 2^{11}$)
MOD => “AND” 21 High−order bits with 0



# Review Questions

***Assume:***

***2 bytes PMT entries; byte addressable MM***

***page & block size = 4 K bytes***

**1) What is the maximum size for any program?**

**2) What PA corresponds to compiled address 220945?**

**2) What is the MBT length if MM size is 80M?**

**(Assume MBT entries are 2 bytes long.)**

**3) What is the PMT length if compiled size = 300K?**

# Allocating Pages

WS

Word size in bytes

P

Page size in Bytes

Size

Size of program in bytes

NPPgm

Num of pages needed for pgm

NPPmt

number of pages needed for PMT

(1 word / entry)

NPTot

Total number of pages needed

MaxBlocks

main memory size, in blocks

```
procedure allocation (int Size) {
     NPpgm  :=  ceiling( Size / P);
     NPmt   :=  ceiling( (NPPgm * WS) / P );
     NPTot    :=  NPPgm + NPPmt;
     If ( NPTot > MaxBlocks )
     Then ERROR
     Else If ( NPTot blocks are not free in MBT )
     Then Add job to HOLDQ;
     Else {
          Allocate pages to blocks;
          Update MBT, PCB;
          Create, initialize PMT;
     }
}
```

# Sharing Pages of Reentrant Code or Data Between Processes

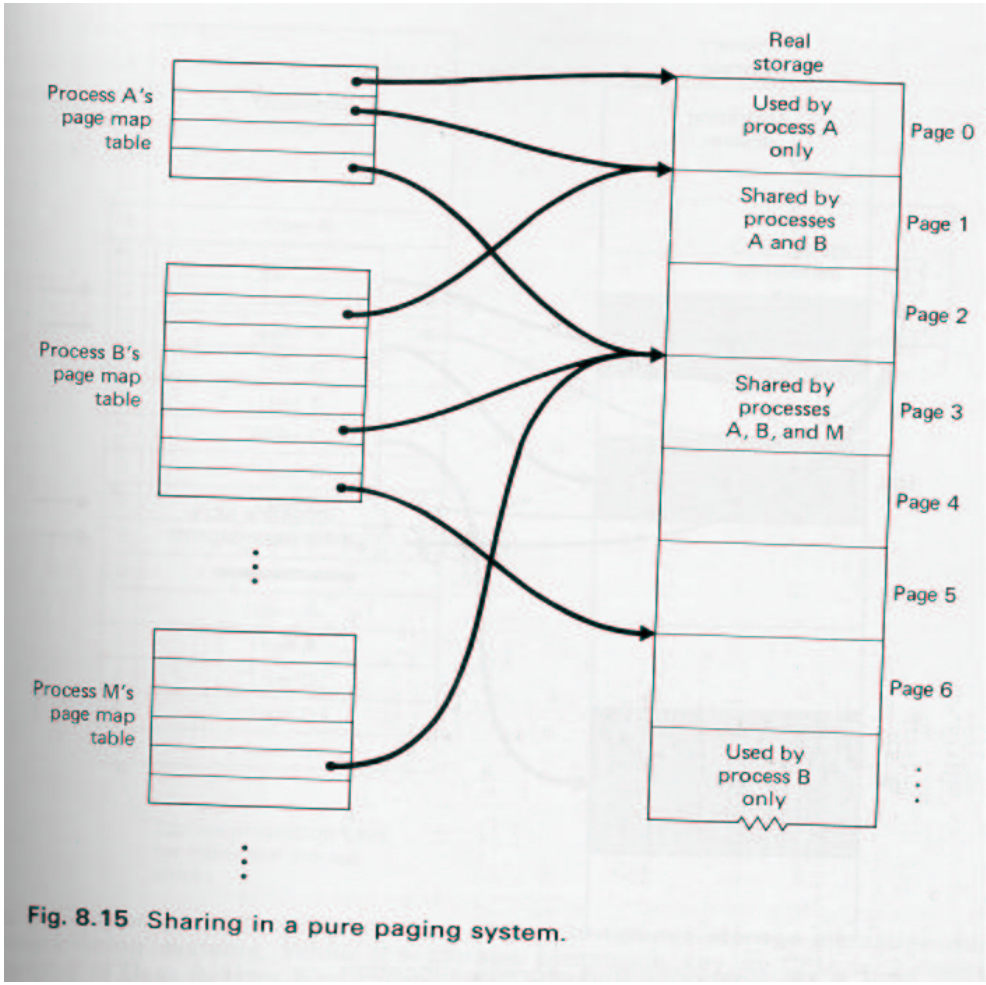



**Fig. 8.15** Sharing in a pure paging system.

# Pros/Cons of Paging

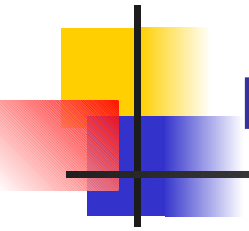
☺ *Advantages:*

- Efficient memory usage
- Simple partition management due to discontiguous loading and fixed partition size
- No compaction necessary
- Easy to share pages

# Pros/Cons of Paging…

☹ *Disadvantages:*

- Job Size <= Memory Size
- Internal fragmentation (half the page size on the average)
- Need special hardware for address translation
- Some main memory space used for PMT's
- Address translation lengthens memory cycle times



# Demand Paging

**Jobs are paged, but not all pages have to be in memory at the same time**

**VIRTUAL MEMORY**

- **The operating system creates the illusion of more memory**
- **Job size can exceed main memory size**

- **Pages are only brought in when referenced (on demand )**
- **Often page 0 is loaded initially when a job is scheduled**

# Demand Paging Motivation

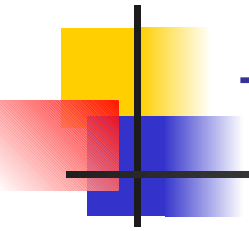
**PMT's**

| | Page | Block |
|---|---|---|
| Job 1 | 0 | 3 |
| | 1 | 5 |
| | 2 | 1 |
| Job 2 | 0 | 2 |
| | 1 | 6 |
| Job 3 | 0 | 4 |
| | 1 | |
| | 2 | |

**MBT**

| | |
|---|---|
| 0 | OS |
| 1 | J1 P2 |
| 2 | J2 P0 |
| 3 | J1 P0 |
| 4 | J3 P0 |
| 5 | J1 P1 |
| 6 | J2 P1 |

1. What happens if job 3 references page 1?
2. What does the CPU do while J3P1 is being read?



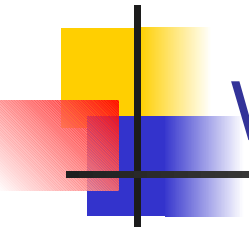
# Terminology

***Page fault*:**

**Interrupt that arises upon a reference to a page that is not in main memory.**

***Page swapping* :**

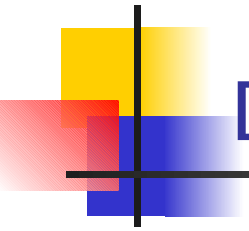
**Replacement of one page in memory by another page in response to a page fault.**



# When a Page Fault Occurs

- Select a page to be removed
- Copy it to disk if it has been changed **
- Update old page's PMT **
- Copy new page to main memory
- Update new page's PMT
- Update MBT **

Thrashing occurs when a job continuously references pages which are not in main memory



# Demand Page Management

**Page Map Table (PMT)**

Maps page to blocks

Status: Pointer to

Main Memory Block

*Indicator*

*Main/Secondary Memory*

**Memory Block Table (MBT)**

Maps block to page

Contains: Job/Page Number

*Reference bit*

*Change bit*

**File Map Table (FMT)**

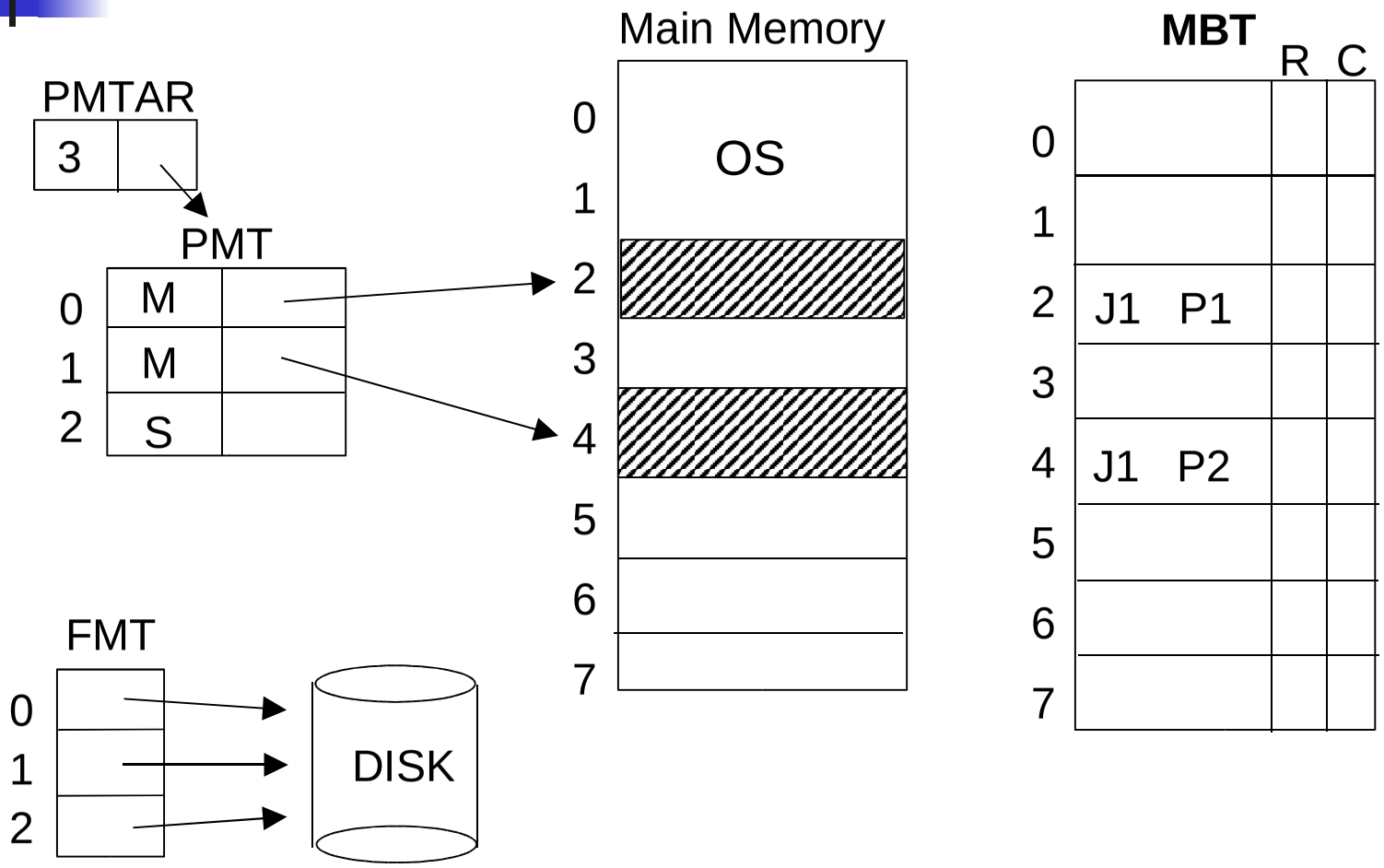
Maps a job's pages to secondary memory

PMT for the Disk

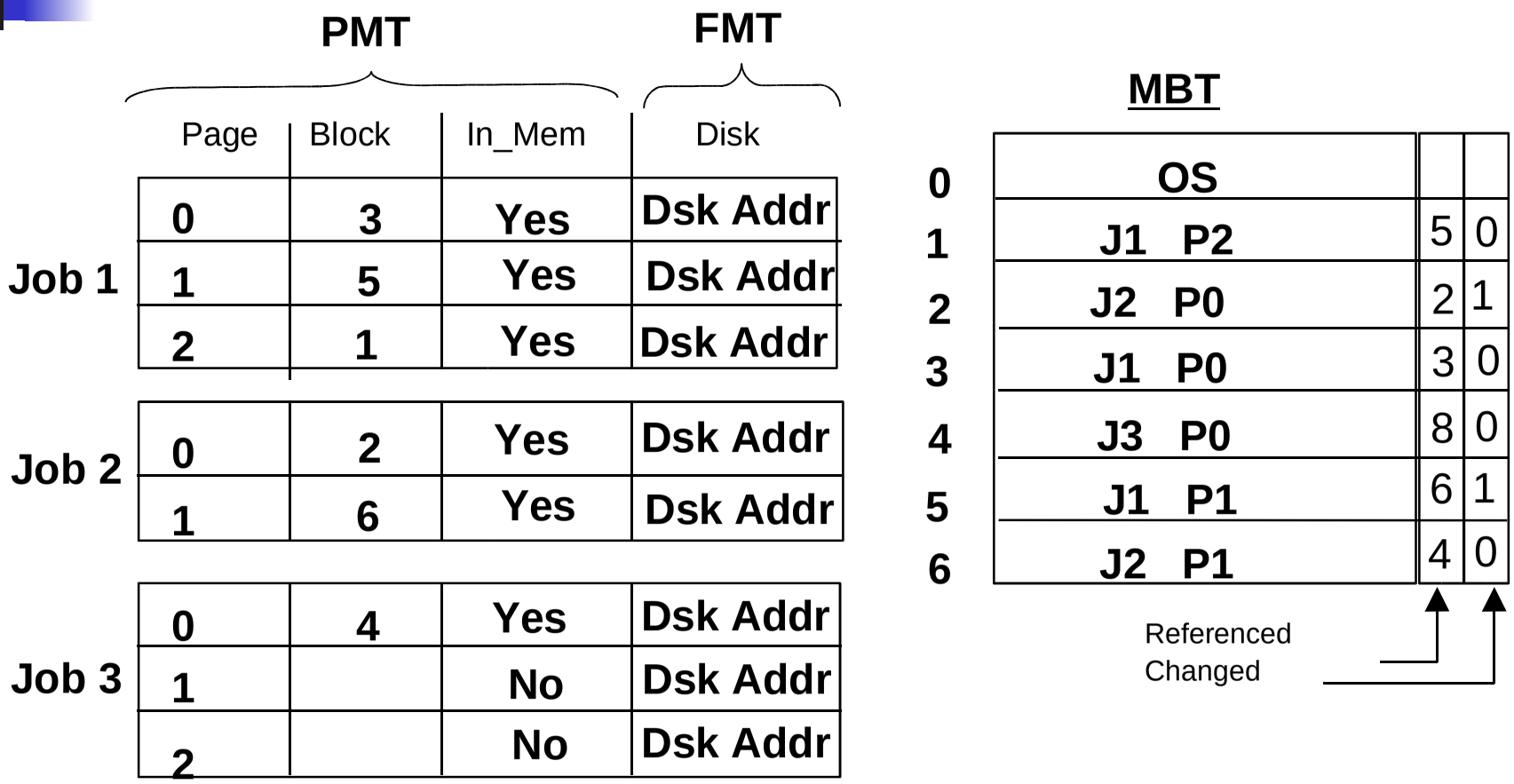
1 FMT / job

1 entry / page

# Demand Paging Schematic



# Demand Paging Data Structures




1. **What happens if job 3 references page 1?**

# Summary of Data Structures

**1) Page Map Table (PMT):** Maps page to block

Fi*elds:* – page number (which page in memory)

– In_Memory <––– New*!*

**2) Memory Block Table (MBT):** Maps block to either process id and page number or to "free"

Fi*elds:* <––– New*!*

– Reference Count

– Change Bit

**3) File Map Table (FMT):** Maps a job's pages to secondary memory (like a PMT for the disk) **<––– *New!***

1 FMT / job, 1 entry / page

# Page Replacement

**Now we consider the decision of selecting *which* page to replace upon a page fault.**

**Local versus Global Page Replacement**

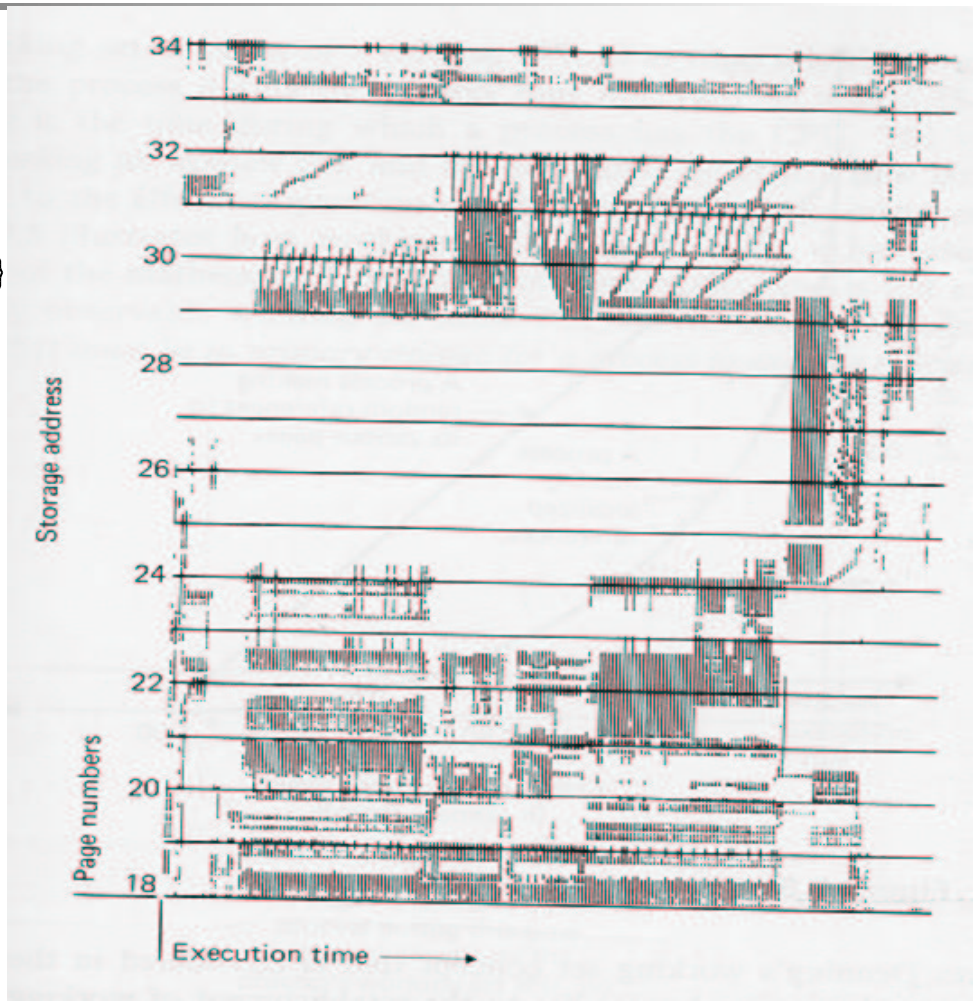
**Local** — **Requires that each process remove a page from its own set of allocated blocks**

**Global** — **A replacement page may be selected from the set of all blocks**

# A Program's Execution Profile

***Question:***

**Does a program need *all* its pages in main memory at all times?**



# The Principle of Locality

At any time, the *locality* of a process is the set of pages that are actively being used together

Spatial — There is a high probability that once a location is referenced, the one after it will be accessed in the near future

Sequential code, Array processing, Code within a loop

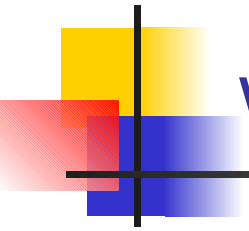
Temporal — A referenced location is likely to be accessed again in the near future

Loop indices, Single data elements

# More on Locality

**Does a linked list help or hurt locality?**

Does a recursive function display spatial or temporal locality?



# Working Set Theory (Formalizes "Locality")

1. A process' **working set** is the number of pages currently being referenced during ( t , t+$\Delta$ ) for some small $\Delta$.
2. The working set size is an estimate of degree of locality
3. A job should not be scheduled unless there is room for its entire working set
    1. Why?

# Idea Behind Working Set

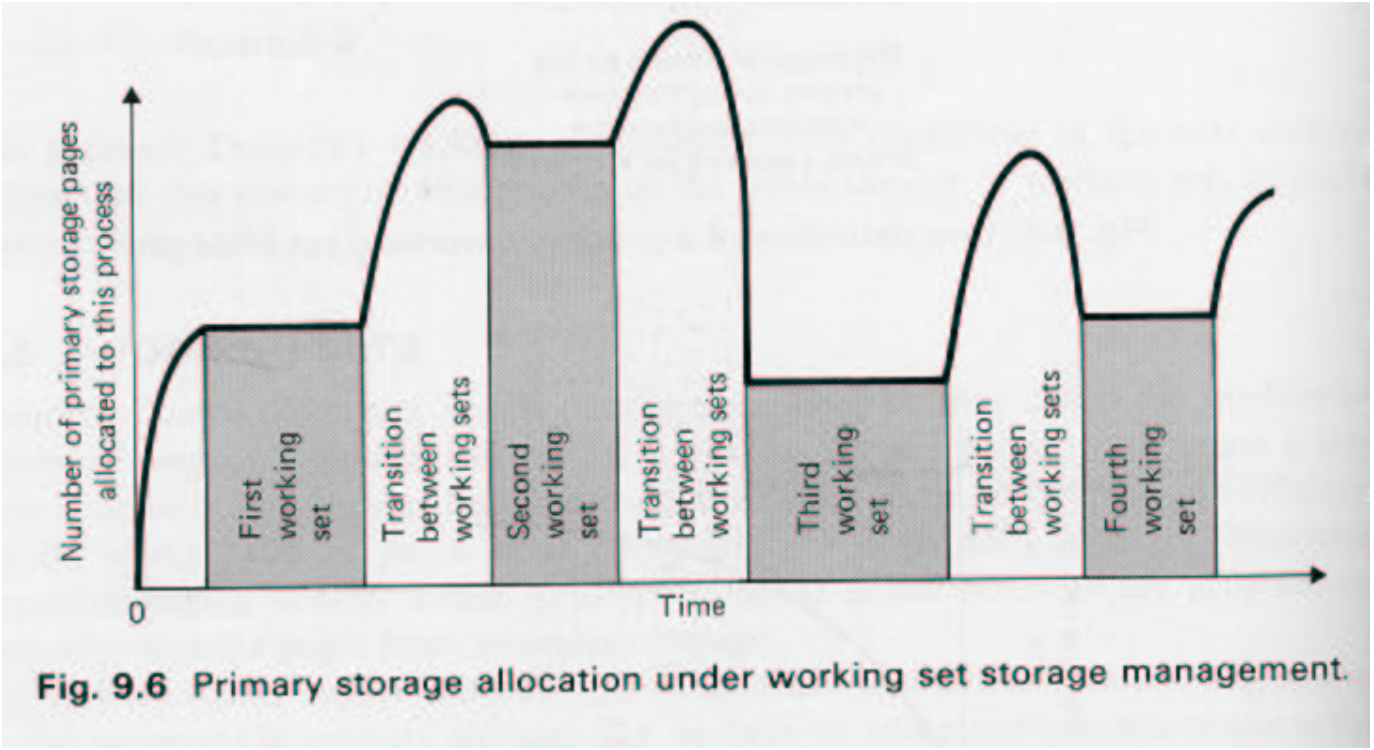
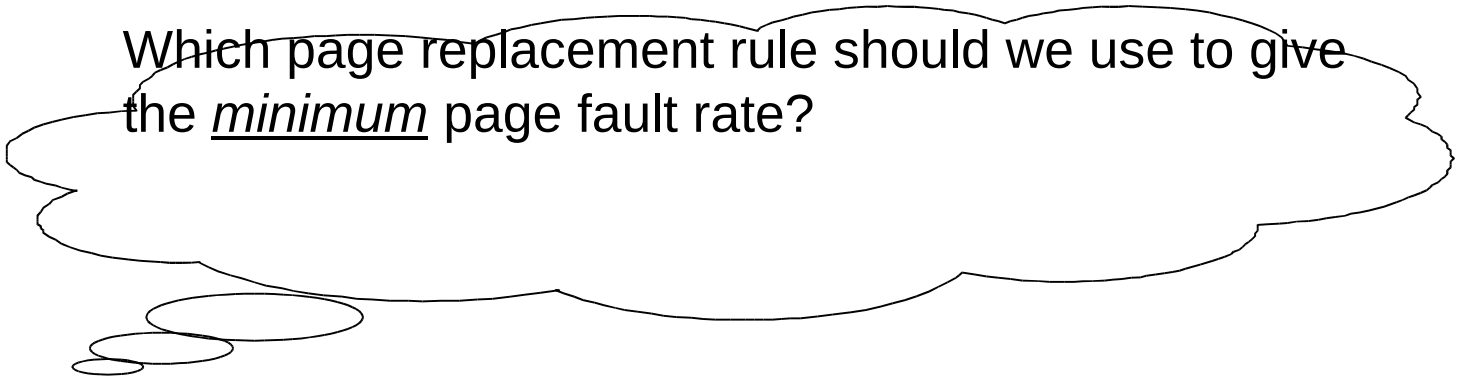



**Fig. 9.6** Primary storage allocation under working set storage management.

# Motivation : Page Replacement Algorithms




**Page fault rate = # faults / #refs**

# Page Replacement Algorithm: **Optimal Replacement**

- Replace the page which will not be used for the longest period of time
- Lowest page fault rate of all algorithms
- Requires knowledge of the future

***Example:***

MM has 3 blocks containing 3,5,2.

Current and future refs:

4, 3, 3, 4, 2, 3, 4, 5, 1, 3, 4

***fault***

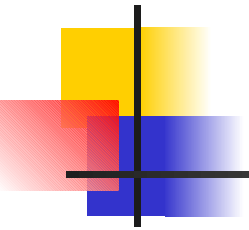
***OPT replaces 5***

# Optimal Replacement Algorithm

| Page Trace: | 0 | 1 | 2 | 3 | 0 | 1 | 4 | 0 | 1 | 2 | 3 | 4 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Block Number 0 | | | | | | | | | | | | |
| Block Number 1 | | | | | | | | | | | | |
| Block Number 2 | | | | | | | | | | | | |

# Page Faults =

Page Fault Rate =



# Replacement Algorithm: **FIFO**

- Replace the "oldest" page
- A frequently used page may be swapped out

***Belady's Anomaly:***

For some page replacement algorithms, the page fault rate may increase as the number of blocks increase

# FIFO Page Replacement

| Page Trace: | 0 | 1 | 2 | 3 | 0 | 1 | 4 | 0 | 1 | 2 | 3 | 4 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Block Number 0 | | | | | | | | | | | | |
| Block Number 1 | | | | | | | | | | | | |
| Block Number 2 | | | | | | | | | | | | |

# Page Faults =

| Page Trace: | 0 | 1 | 2 | 3 | 0 | 1 | 4 | 0 | 1 | 2 | 3 | 4 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Block Number 0 | | | | | | | | | | | | |
| Block Number 1 | | | | | | | | | | | | |
| Block Number 2 | | | | | | | | | | | | |
| Block Number 3 | | | | | | | | | | | | |

# Page Faults =

# Replacement Algorithms: **Least Recently Used (LRU)**

- Uses the recent past as an approximation of the near future
- Stack algorithm
  - Does NOT suffer from Belady's Anomaly
- Hardware / Overhead intensive

# Least Recently Used (LRU)

| Page Trace: | 0 | 1 | 2 | 3 | 0 | 1 | 4 | 0 | 1 | 2 | 3 | 4 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Block Number 0 | | | | | | | | | | | | |
| Block Number 1 | | | | | | | | | | | | |
| Block Number 2 | | | | | | | | | | | | |

# Page Faults =

| Page Trace: | 0 | 1 | 2 | 3 | 0 | 1 | 4 | 0 | 1 | 2 | 3 | 4 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Block Number 0 | | | | | | | | | | | | |
| Block Number 1 | | | | | | | | | | | | |
| Block Number 2 | | | | | | | | | | | | |
| Block Number 3 | | | | | | | | | | | | |

# Page Faults =

# Replacement Algorithms: **LRU Approximation**

- Uses reference bits in the MBT and a static reference pointer (RP)
- The reference pointer is not reinitialized between calls to LRU Approximation
- Set referenced bit to 1 when loading a page
- Set referenced bit to 1 on a R/W
- Set referenced bit to 0 if currently a 1 and scanning for a replacement page
- Replace page with reference bit = 0

# LRU Approximation Algorithm…

**Initially: RP <– –1**

```
begin
RP := (RP + 1) mod MBTSize;
While (MBT[RP].Referenced = 1 Do
Begin
MBT[RP].Referenced  :=  0
RP := (RP + 1) mod MBTSize;
End
return(RP);
```

**Note: referenced bit is set to 1 when a page is**
**(a) referenced, and**
**(b) when first loaded into memory**

**RP always points to last page replaced**

# LRU Approximation

| Page Trace: | 0 | 1 | 2 | 3 | 0 | 1 | 4 | 0 | 1 | 2 | 3 | 4 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Block Number 0 | | | | | | | | | | | | |
| Block Number 1 | | | | | | | | | | | | |
| Block Number 2 | | | | | | | | | | | | |

# Page Faults =

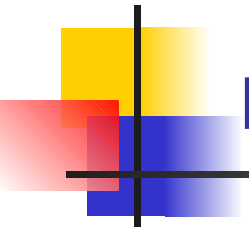
Page Fault Rate =

# Replacement Algorithms: Least Frequently Used (LFU)

- Keep a reference count, select page with lowest count
- Reference count is number of times a page has been referenced over its **current** stay in memory, **not** over the lifetime of the program

| Page Trace: | 0 | 1 | 2 | 3 | 0 | 1 | 4 | 0 | 1 | 2 | 3 | 4 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Block Number 0 | | | | | | | | | | | | |
| Block Number 1 | | | | | | | | | | | | |
| Block Number 2 | | | | | | | | | | | | |

# Page Faults =



# Pros/Cons of Demand Paging

- A*dvantages:*

1. Can run program larger than physical memory
2. Allows higher multiprogramming level than pure paging
3. Efficient memory usage
4. No compaction is required
5. Portions of process that are never called are never loaded
6. Simple partition management due to discontinuous loading and fixed partition size
7. Easy to share pages

# Pros/Cons of Demand Paging…

☹ *Disadvantages:*

1. Internal fragmentation
2. Program turnaround time increases each time a page is replaced, then reloaded
3. Need special address translation hardware