




Operating System Concepts

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Contents

1. Introduction
2. System Structures
3. Process Concept
4. Multithreaded Programming
5. Process Scheduling
6. Synchronization
7. Deadlocks
8. Memory-Management Strategies
-  9. Virtual-Memory Management
10. File System
11. Implementing File Systems
12. Secondary-Storage Systems





Chapter 9. Virtual- Memory Management

Objectives

- ▶ To describe the benefits of a virtual memory system
- ▶ To explain the concepts of demand paging, page-replacement algorithms, and allocation of page frames
- ▶ To discuss the principle of the working-set model



Background

▶ Virtual Memory

- A technique that allows the execution of a process that may not be completely in memory

▶ Motivation

- An entire program in execution may not all be needed at the same time
 - Error handling routines
 - A large array

Virtual Memory

► Potential Benefits

- Programs can be much larger than the amount of physical memory
 - Users can concentrate on their problem programming
- The level of multiprogramming increases because processes occupy less physical memory
- Each user program may run faster because less I/O is needed for loading or swapping user programs

► Implementation: demand paging

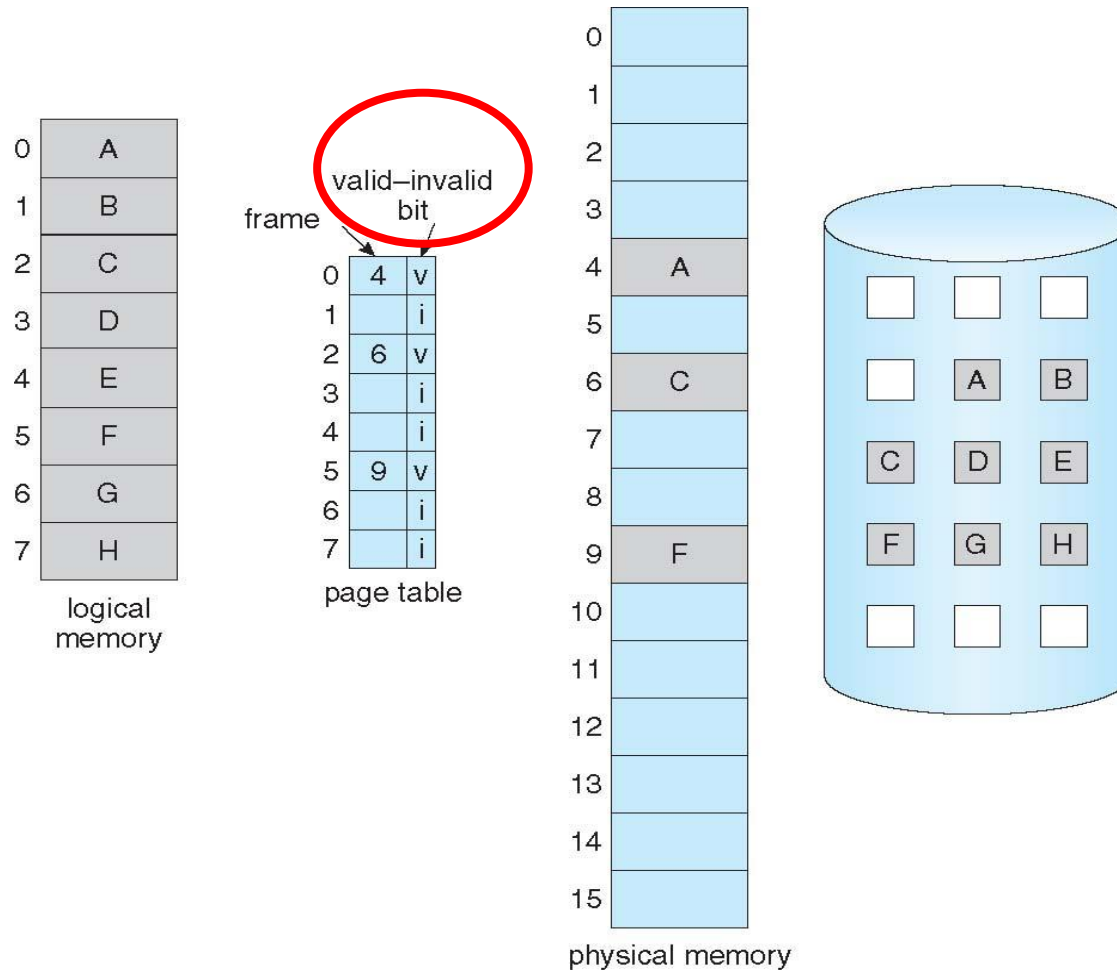
Demand Paging– Lazy Swapper

- ▶ Process image may reside on the backing store
 - Rather than swap in the entire process image into memory
Lazy Swapper only swaps in a page when it is needed
- ▶ A mechanism is required to recover from the missing of non-resident referenced pages
 - A **Page Fault** occurs when a process references a non-memory-resident page

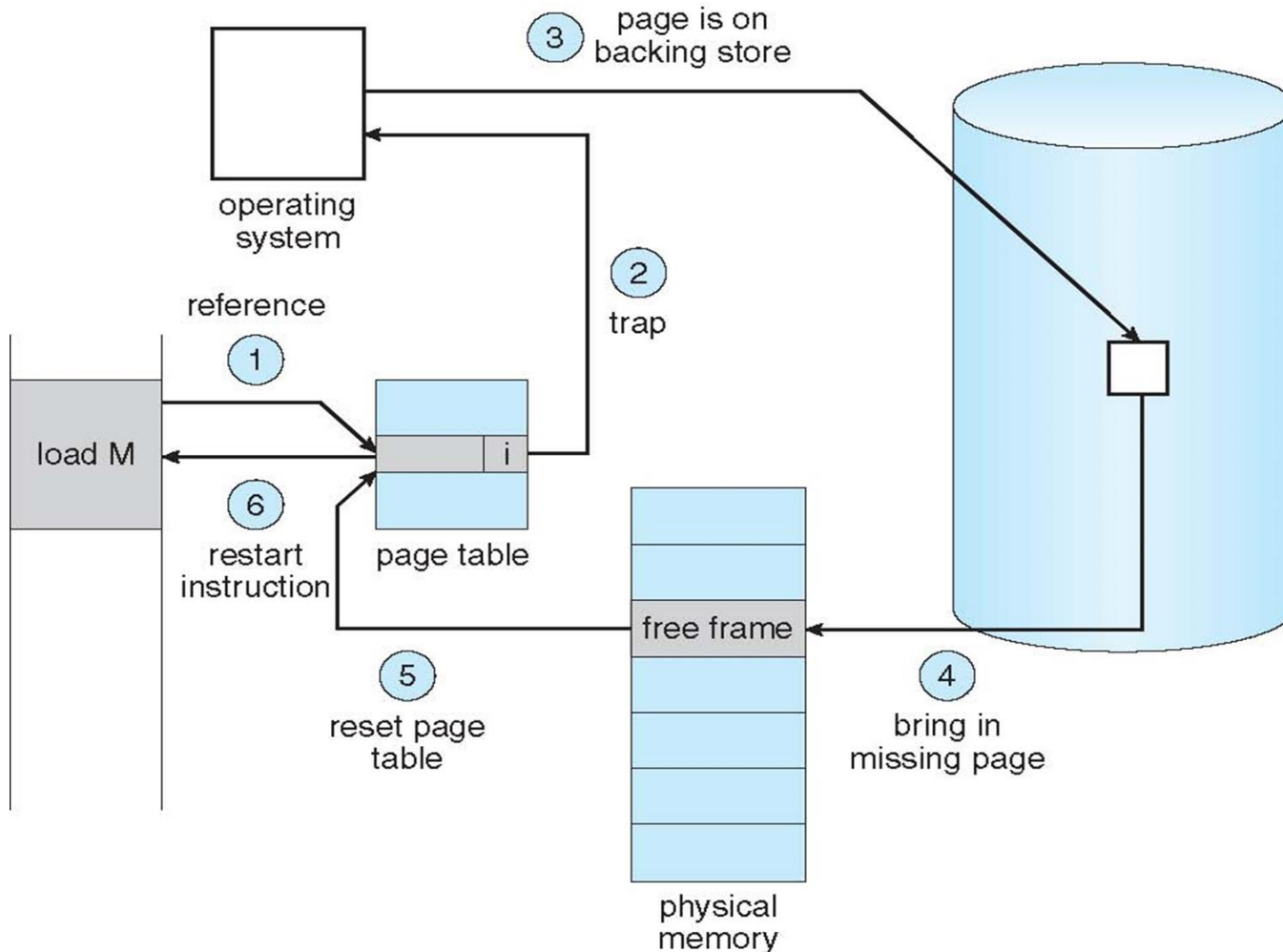
Hardware Support for Demand Paging

- ▶ New bits in the page table
 - To indicate that a page is now in memory or not
- ▶ Secondary storage management
 - Swap space in the backing store
 - A continuous section of space in the secondary storage for better performance

Valid-Invalid Bits



Steps in Handling a Page Fault



Copy-on-Write

- ▶ **Copy-on-Write** (COW) allows both parent and child processes to initially *share* the same pages in memory
 - If either process modifies a shared page, then the page is copied
- ▶ COW allows more efficient process creation as only modified pages are copied
- ▶ In general, free pages are allocated from a **pool** of **zero-fill-on-demand** pages

Performance of Demand Paging

- ▶ Page Fault Rate $0 \leq p \leq 1$
 - if $p = 0$ no page faults
 - if $p = 1$, every reference is a fault

- ▶ Effective Access Time (EAT)

$$\begin{aligned} \text{EAT} = & (1 - p) \times \text{memory-access time} \\ & + p (\text{page fault overhead} \\ & \quad + \text{swap page out} \\ & \quad + \text{swap page in} \\ & \quad + \text{restart overhead}) \end{aligned}$$



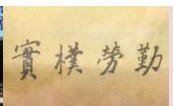
An Example of Demand Paging

- ▶ Memory access time = 200 nanoseconds
- ▶ Average page-fault service time = 8 milliseconds
- ▶ $EAT = (1 - p) \times 200 + p \times 8,000,000$
 $= 200 + p \times 7,999,800$
- ▶ If one access out of 1,000 causes a page fault, then
 $EAT = 8.2$ microseconds!
- ▶ If we want performance degradation < 10 percent
 - $220 > 200 + 7,999,800 \times p$
 - $p < 0.0000025$



Performance Improvement of Demand Paging

- ▶ Preload processes into the swap space before they start up
- ▶ Preload pages into the main memory before the pages are used
- ▶ Design a good page replacement algorithm



Algorithms for Demand Paging

- ▶ Frame Allocation Algorithms
 - How many frames are allocated to a process?
- ▶ Page Replacement Algorithms
 - When page replacement is required, select the frame that is to be replaced!
- ▶ Goal: A low page fault rate!



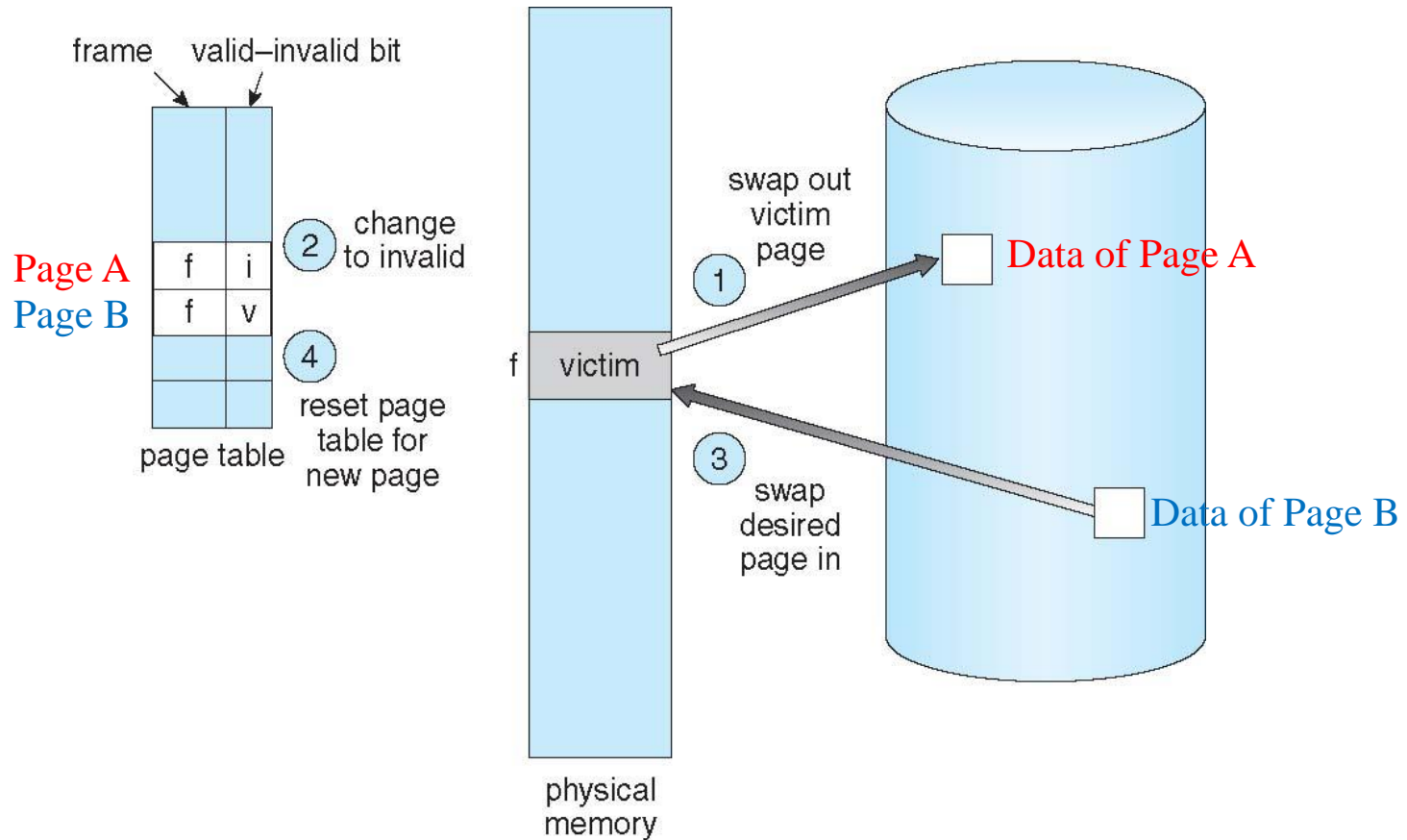
Page Replacement

- ▶ Demand paging increases the multiprogramming level of a system by “potentially” over-allocating memory
 - Total physical memory = 40 frames
 - Run six processes of size equal to 10 frames
 - Each process currently uses only 5 frames
 - ➔ 10 spare frames
- ▶ Most of the time, the average memory usage is close to the physical memory size if we increase a system’s multiprogramming level



Victim Pages

What happens if there is no free frame?



A Page-Fault Service

- ▶ Find the desired page on the disk
- ▶ Find a free frame
 - Select a victim and write the victim page out when there is no free frame
- ▶ Read the desired page into the selected frame
- ▶ Update the page and frame tables, and restart the user process



Page Replacement — FIFO Algorithm

► First In First Out (FIFO) Implementation

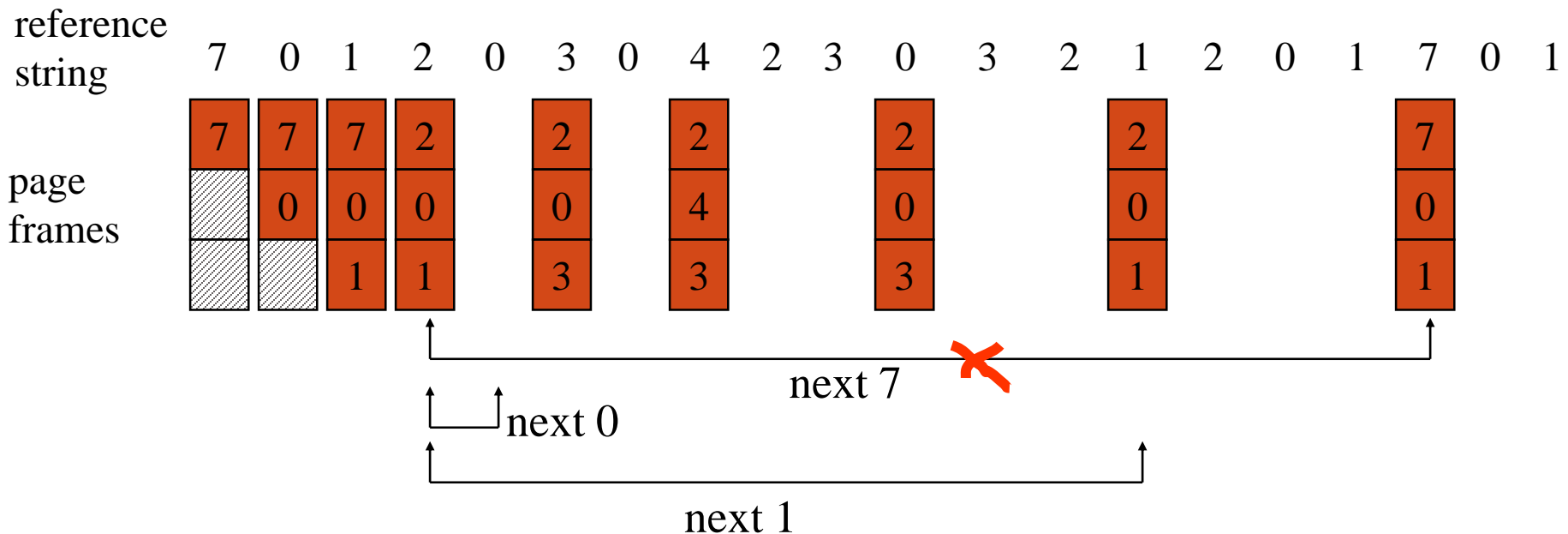
1. Each page is given a time stamp when it is brought into memory
2. Select the oldest page for replacement

reference string	7	0	1	2	0	3	0	4	2	3	0	3	2	1	2	0	1	7	0	1
page frames	<div>7</div>	<div>7</div>	<div>7</div>	<div>2</div>		<div>2</div>	<div>2</div>	<div>4</div>	<div>4</div>	<div>4</div>	<div>0</div>			<div>0</div>	<div>0</div>			<div>7</div>	<div>7</div>	<div>7</div>
	<div></div>	<div>0</div>	<div>0</div>	<div>0</div>		<div>3</div>	<div>3</div>	<div>3</div>	<div>2</div>	<div>2</div>	<div>2</div>			<div>1</div>	<div>1</div>			<div>1</div>	<div>0</div>	<div>0</div>
	<div></div>	<div></div>	<div>1</div>	<div>1</div>		<div>1</div>	<div>0</div>	<div>0</div>	<div>0</div>	<div>3</div>	<div>3</div>			<div>3</div>	<div>2</div>			<div>2</div>	<div>2</div>	<div>1</div>
FIFO queue	7	7	7	0		1	2	3	0	4	2			3	0			1	2	7
		0	0	1		2	3	0	4	2	3			0	1			2	7	0
			1	2		3	0	4	2	3	0			1	2			7	0	1



Page Replacement — Optimal Algorithm

- ▶ Optimality
 - One with the lowest page fault rate
- ▶ Replace the page that will not be used for the longest period of time → It needs future prediction



Page Replacement — Least-Recently-Used Algorithm

- ▶ Least-Recently-Used Algorithm (LRU)
 - We don't have knowledge about the future
 - Thus, we use the history of page referencing in the past to predict the future

➔ However, it is too expensive to update the time stamp for each memory access!

reference string	7	0	1	2	0	3	0	4	2	3	0	3	2	1	2	0	1	7	0	1
page frames	7 	7 0 	7 0 1	2 0 1	 	2 0 3	 	4 0 3	4 0 2	4 3 2	0 3 2	 	 	1 3 2	 	 	1 0 2	 	1 0 7	
LRU queue	7	0	1	2	0	3	0	4	2	3	0	3	2	1	2	0	1	7	0	1
		7	0	1	2	0	3	0	4	2	3	0	3	2	1	2	0	1	7	0
			7	0	1	2	2	3	0	4	2	2	0	3	3	1	2	0	1	7

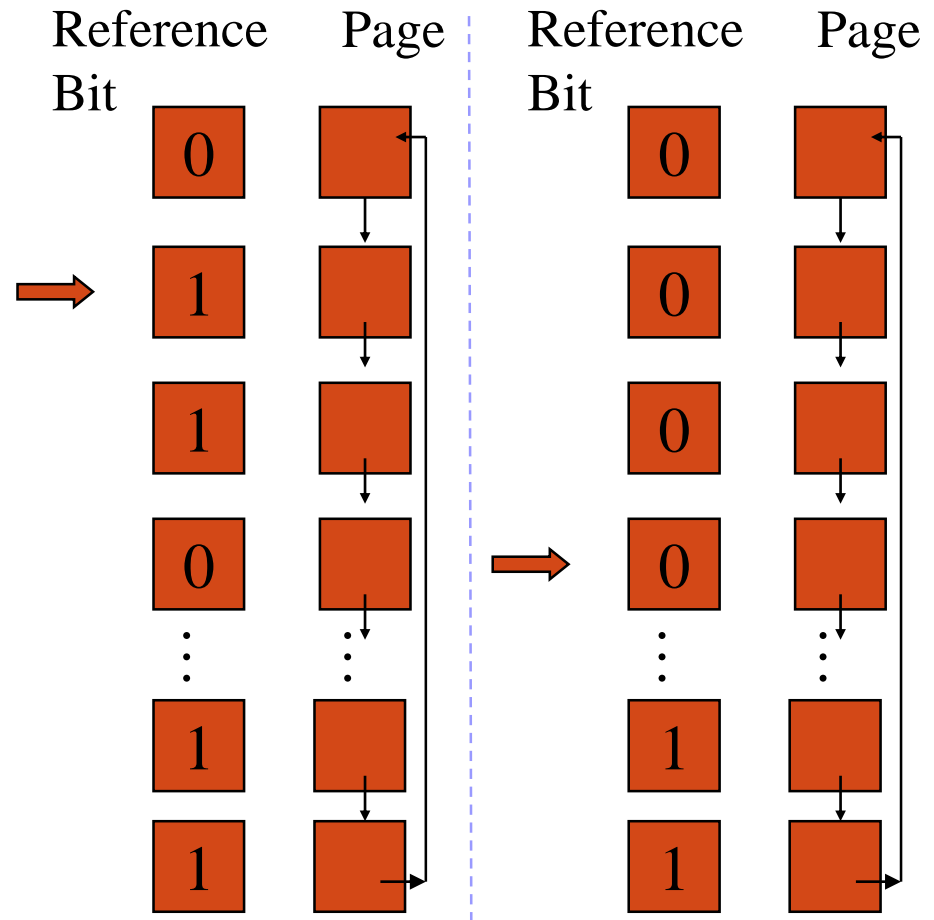
Page Replacement — LRU Approximation Algorithms

▶ Second-Chance Algorithm

- When a page is selected
 - Take it as a victim if its reference bit = 0
 - Otherwise, clear the bit and advance to the next page

▶ Basic Data Structure

- Use a reference bit for each page in memory
- Define a circular FIFO queue of pages



Enhanced Second-Chance Algorithm

- ▶ Considering the reference bit and the modify bit as an ordered pair
 - (0, 0) neither recently used nor modified – best page to replace
 - (0, 1) not recently used but modified – the page will need to be written out before replacement
 - (1, 0) recently used but clean – probably will be used again soon
 - (1, 1) recently used and modified - probably will be used again soon, and the page will need to be written out to disk before it can be replaced
- ▶ We replace the first page encountered in the lowest nonempty class

Low
Priority
↓
High
Priority



Counting-Based Algorithms

- ▶ Motivation:
 - Count the number of references made to each page, instead of their referencing times
- ▶ Least Frequently Used Algorithm (LFU)
 - LFU pages are less actively used pages
 - Hazard: Some heavily used pages may no longer be used
 - A Solution – Aging
 - Pages with the smallest number of references are probably just brought in and has yet to be used
- ▶ Most Frequently Used Algorithm (MFU)
- ▶ LFU & MFU replacement schemes can be fairly expensive
- ▶ They do not approximate OPT very well



Page Buffering

- ▶ Basic Idea: to reduce the latency for writing victims out
 - Systems keep a pool of free frames
 - Desired pages are first “swapped in” some frames in the pool
 - When the selected page (victim) is later written out, its frame is returned to the pool
- ▶ Basic Approach
 - Maintain a list of modified pages
 - Whenever the paging device is idle, a modified page is written out and reset its “modify bit”
 - The clean pages can be included in the pool



Allocation of Frames (1 / 2)

- ▶ Each process needs minimum number of frames
- ▶ Example: IBM 370 – 6 pages to handle SS MOVE instruction:
 - instruction is 6 bytes, might span 2 pages
 - 2 pages to handle *from*
 - 2 pages to handle *to*
- ▶ Maximum of course is total frames in the system
- ▶ Fixed allocation
 - Use a formula to derive the number of required frames for each application
- ▶ Dynamic allocation
 - Measure some behavior, e.g. page fault rate, to know the needs of applications



Allocation of Frames (2 / 2)

▶ Global Allocation

- Processes can take frames from others
- For example, high-priority processes can increase its frame allocation at the expense of the low-priority processes

▶ Local Allocation

- Processes can only select frames from their own allocated frames
- The set of pages in memory for a process is affected by the paging behavior of only that process



Non-Uniform Memory Access

- ▶ Many systems are NUMA – speed of access to memory varies
 - Consider system boards containing CPUs and memory, interconnected over a system bus
- ▶ Optimal performance comes from allocating memory “close to” the CPU on which the thread is scheduled
 - Modifying the scheduler to schedule the thread on the same CPU when possible

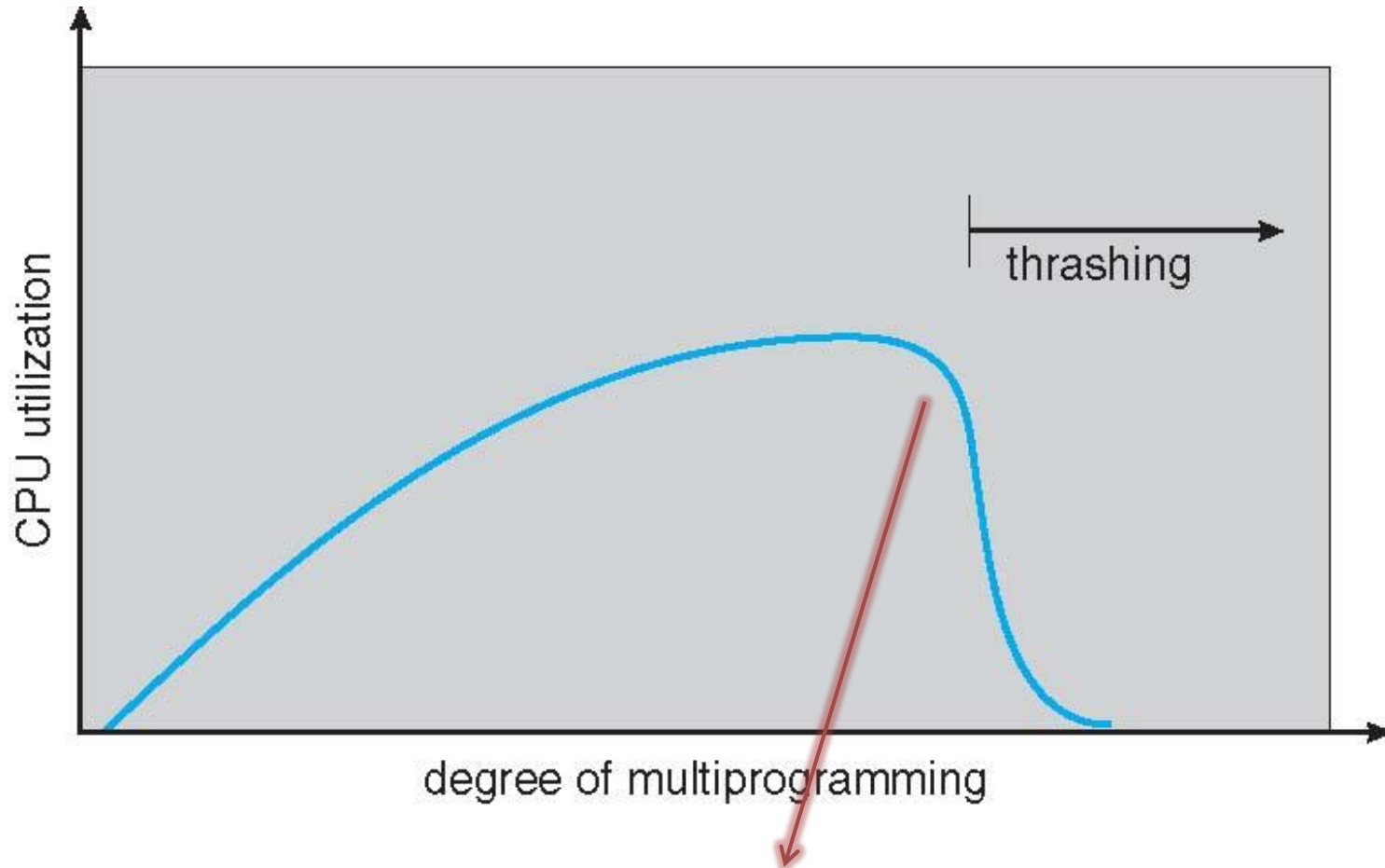


Thrashing (1 / 2)

- ▶ If a process does not have “enough” memory frames, the page-fault rate is very high
 - Page fault to get pages into memory frames
 - Replace existing pages in frames
 - But soon need to get the replaced pages back
 - This leads to:
 - Low CPU utilization
 - Operating system is then thinking that it needs to increase the degree of multiprogramming
 - Another processes are added to the system
 - More page faults
- ▶ **Thrashing** → Process is busy swapping pages in and out



Thrashing (2/2)

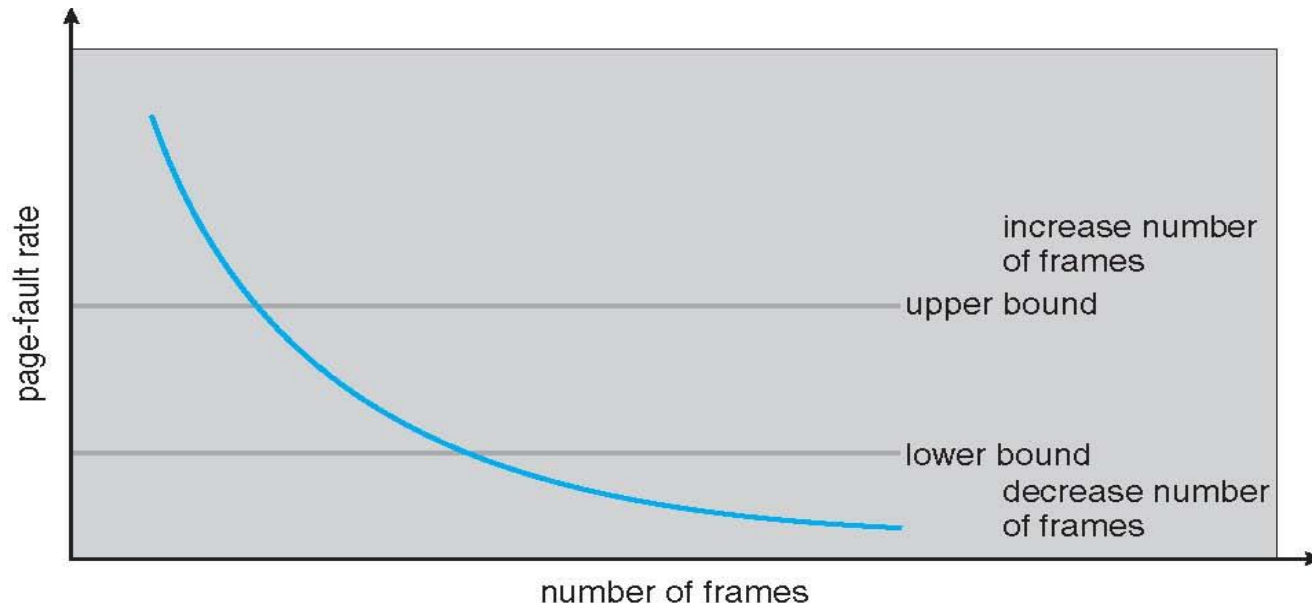


Be careful of the page fault rate



Page-Fault Frequency

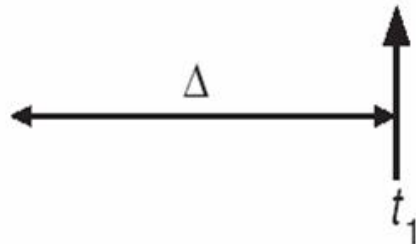
- ▶ Establish “acceptable” page-fault frequency rate and use local replacement policy
 - Control thrashing directly through the observation on the page-fault rate
 - If actual rate too low, process loses frame
 - If actual rate too high, process gains frame



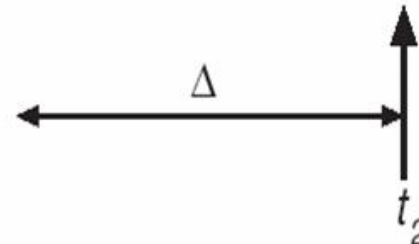
Working-Set Model (1 / 2)

page reference table

... 2 6 1 5 7 7 7 7 5 1 6 2 3 4 1 2 3 4 4 4 4 3 4 3 4 4 4 4 1 3 2 3 4 4 4 3 4 4 4 ...



$$WS(t_1) = \{1, 2, 5, 6, 7\}$$



$$WS(t_2) = \{3, 4\}$$



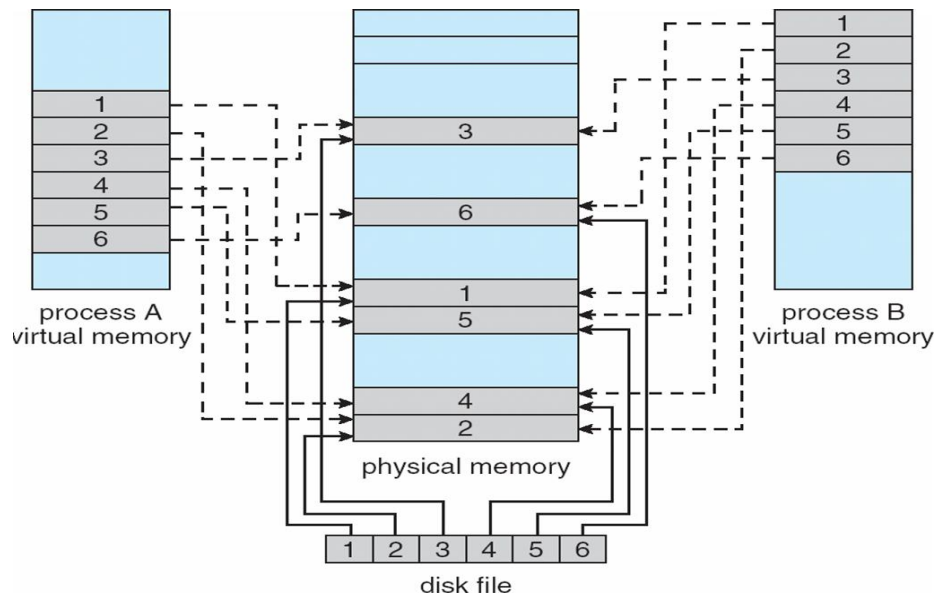
Working-Set Model (2 / 2)

- ▶ $\Delta \equiv$ a working-set window \equiv a fixed number of page references
 - Example: 10,000 instructions
- ▶ WSS_i (working set of Process P_i) = total number of pages referenced in the most recent Δ
 - if Δ is too small: will not encompass entire locality
 - if Δ is too large: will encompass several localities
 - if $\Delta = \infty$: will encompass entire program
- ▶ $D = \sum WSS_i \equiv$ total demand frames
 - Approximation of locality
- ▶ if $D > \text{the number of frames} \rightarrow$ Thrashing



Memory-Mapped Files

- ▶ Memory-mapped file I/O allows file I/O to be treated as routine memory access by **mapping** a disk block to a page in memory
 - But when does written data make it to disk?
 - Periodically and/or at file `close()` time



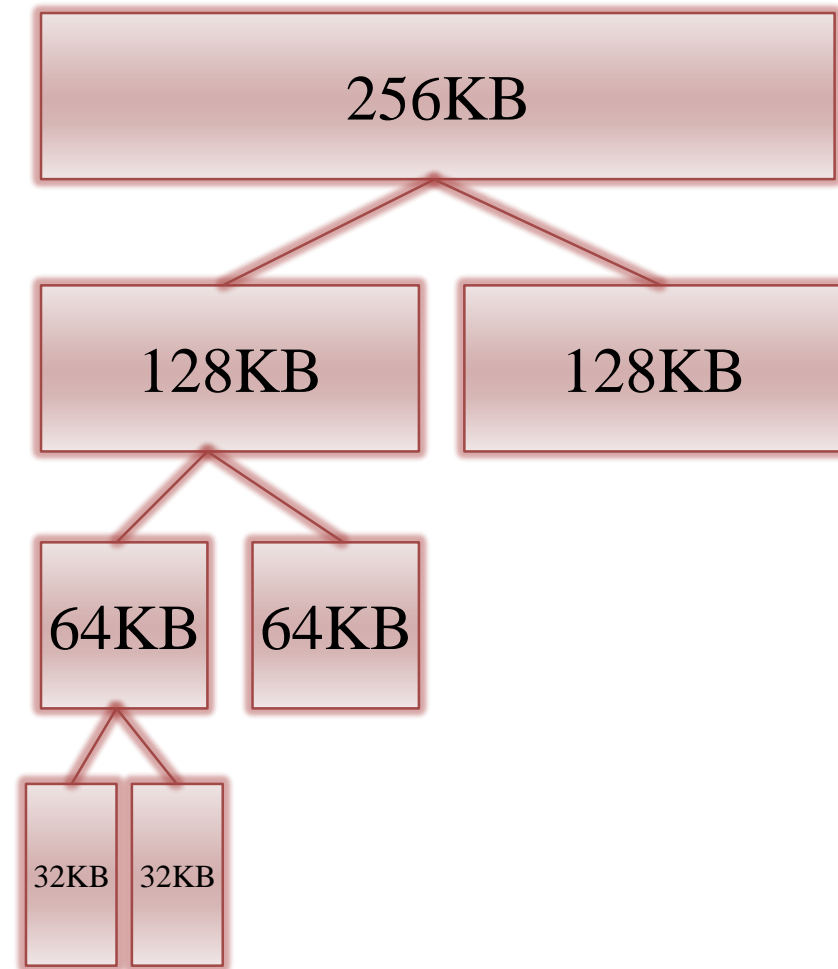
Memory-Mapped I/O

- ▶ Processor can have direct access
- ▶ Memory-Mapped I/O
 - (1) Frequently used devices
 - (2) Devices must be fast, such as video controller, or special I/O instructions are used to move data between memory & device controller registers
- ▶ Programmed I/O – polling
 - or interrupt-driven handling



Kernel Memory Allocation (1 / 2)

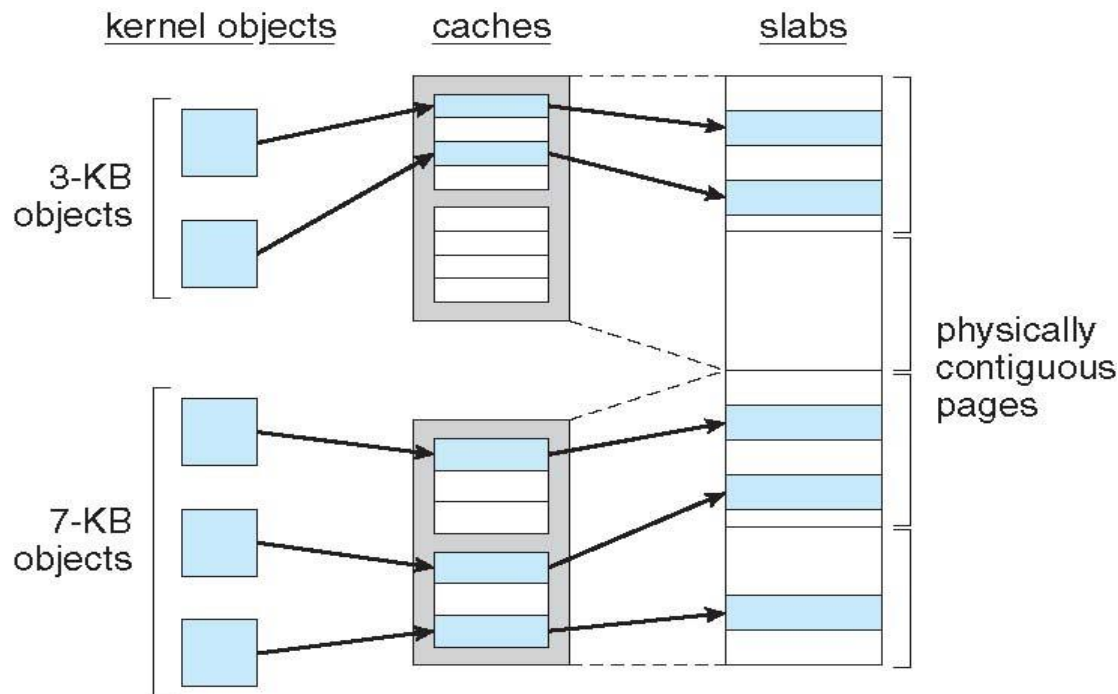
- ▶ The Buddy System
 - A fixed-size segment of physically contiguous pages
 - A power-of-2 allocator
 - Advantage: quick coalescing algorithms
 - Disadvantage: internal fragmentation



Kernel Memory Allocation (2/2)

► Slab Allocation

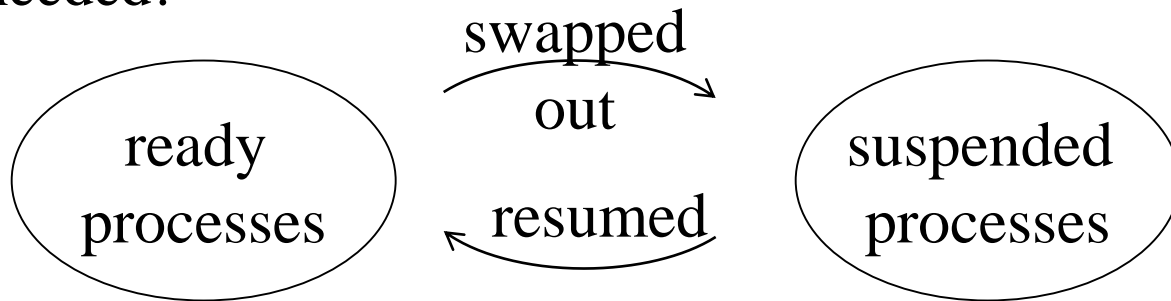
- Slab: one or more physically contiguous pages
- Cache: one or more slabs with the same size



Other Considerations: Pre-Paging

► Pre-Paging

- Bring into memory at one time all the pages that will be needed!



Do pre-paging if the working set is known!

► Issue

Pre-Paging Cost \longleftrightarrow Cost of Page Fault Services

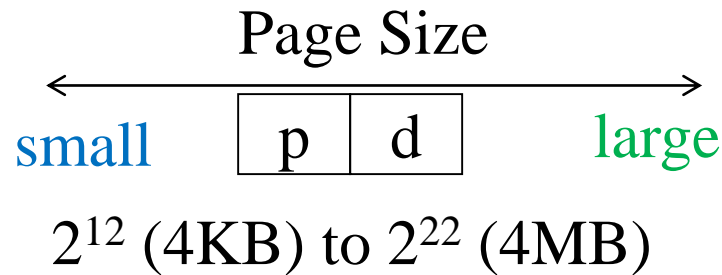
Not every page in the working set will be used!



Other Considerations: Page Size

► Page Size

Better
Resolution
for Locality &
Internal
Fragmentation



Smaller Page
Table Size &
Better I/O
Efficiency

- Trends: Large Page Size
 - ∴ The CPU speed and the memory capacity grow much faster than the disk speed!



Other Considerations: TLB Reach

- ▶ TLB Reach - The amount of memory accessible from the TLB
- ▶ $\text{TLB Reach} = (\text{TLB Size}) \times (\text{Page Size})$
- ▶ Ideally, the working set of each process is stored in the TLB
 - Otherwise there is a high degree of page faults
- ▶ Increase the Page Size
 - This may lead to an increase in fragmentation as not all applications require a large page size



Other Considerations: Program Structures

► Program Structures:

- `int data [1024][1024];`
- Each row is stored in one page
- Program 1

```
for (j = 0; j < 1024; j++)  
    for (i = 0; i < 1024; i++)  
        data[i][j] = 0;
```

1024 x 1024 page faults

- Program 2

```
for (i = 0; i < 1024; i++)  
    for (j = 0; j < 1024; j++)  
        data[i][j] = 0;
```

1024 page faults



Other Considerations: I/O Interlock

- ▶ **I/O Interlock** – Pages must sometimes be locked into memory
- ▶ Consider I/O - Pages that are used for copying a file from a device must be locked from being selected for eviction by a page replacement algorithm

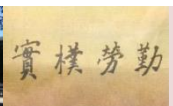




File Concepts

File Attributes

- ▶ **Name** – only information kept in human-readable form
- ▶ **Identifier** – unique tag (number) identifies file within file system
- ▶ **Type** – needed for systems that support different types
- ▶ **Location** – pointer to file location on device
- ▶ **Size** – current file size
- ▶ **Protection** – controls who can do reading, writing, executing
- ▶ **Time, date, and user identification** – data for protection, security, and usage monitoring
- ▶ Information about files are kept in the directory structure, which is maintained on the disk
- ▶ Many variations, including extended file attributes such as file checksum



File Operations

- ▶ File is an **abstract data type**
- ▶ **Create**
- ▶ **Write** – at **write pointer** location
- ▶ **Read** – at **read pointer** location
- ▶ **Reposition within file - seek**
- ▶ **Delete**
- ▶ **Truncate**
- ▶ *Open(F_i)* – search the directory structure on disk for entry F_i , and move the content of entry to memory
- ▶ *Close (F_i)* – move the content of entry F_i in memory to directory structure on disk

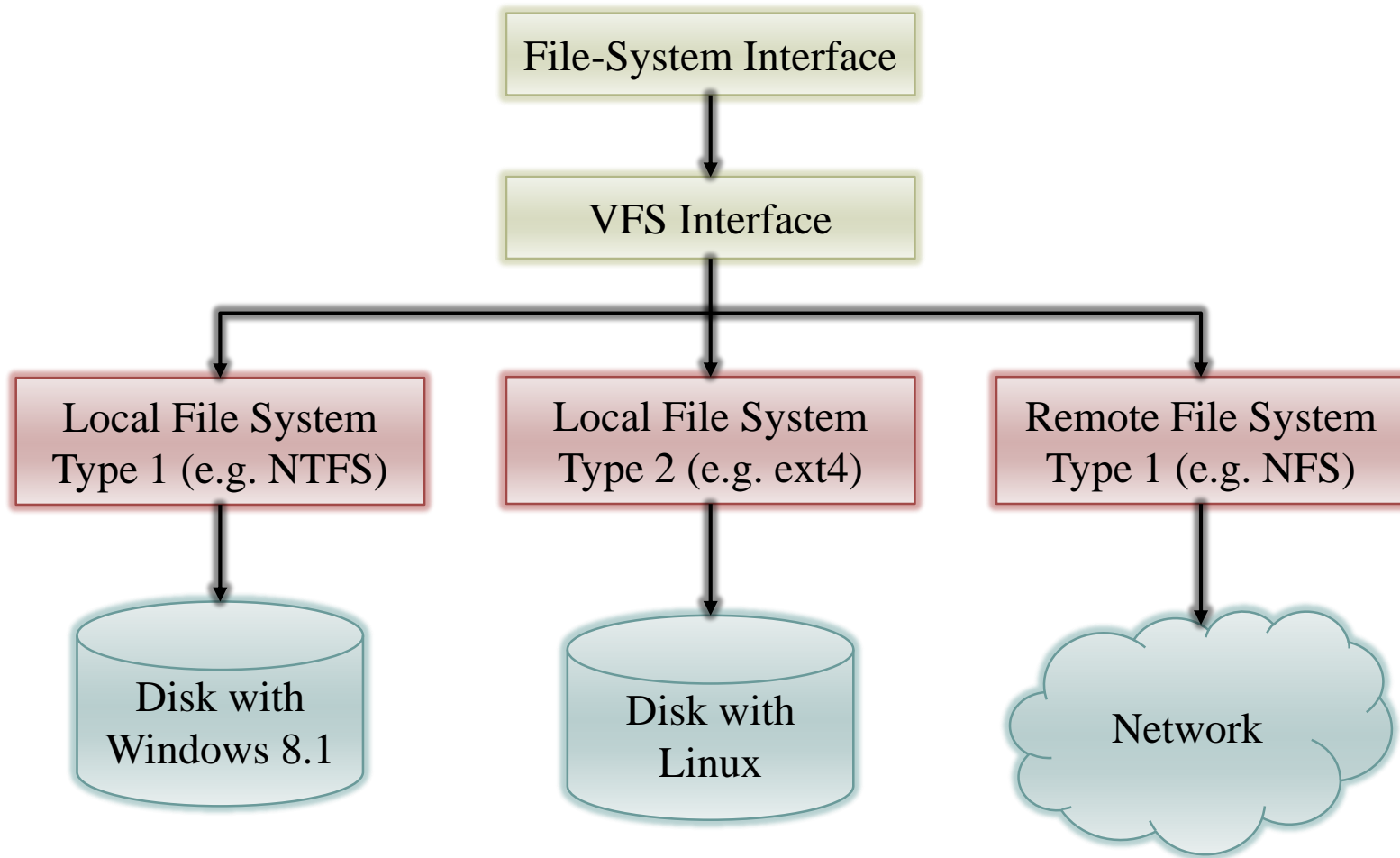


File Systems

- ▶ Microsoft Windows File Systems
 - FAT
 - NTFS
 - exFAT
- ▶ Linux File Systems
 - ext2
 - ext3
 - ext4
 - JFFS → for Flash devices
- ▶ Network File Systems
 - NFS
 - Samba



Schematic View of Virtual File System



Virtual File System

- ▶ Virtual File Systems (VFS) on provide an object-oriented way of implementing file systems
- ▶ VFS allows the same system call interface (the API) to be used for different types of file systems
 - Separates file-system generic operations from implementation details
 - Implementation can be one of many file systems types, or network file system
 - Then dispatches operation to appropriate file system implementation routines
- ▶ The API is to the VFS interface, rather than any specific type of file system



Contents

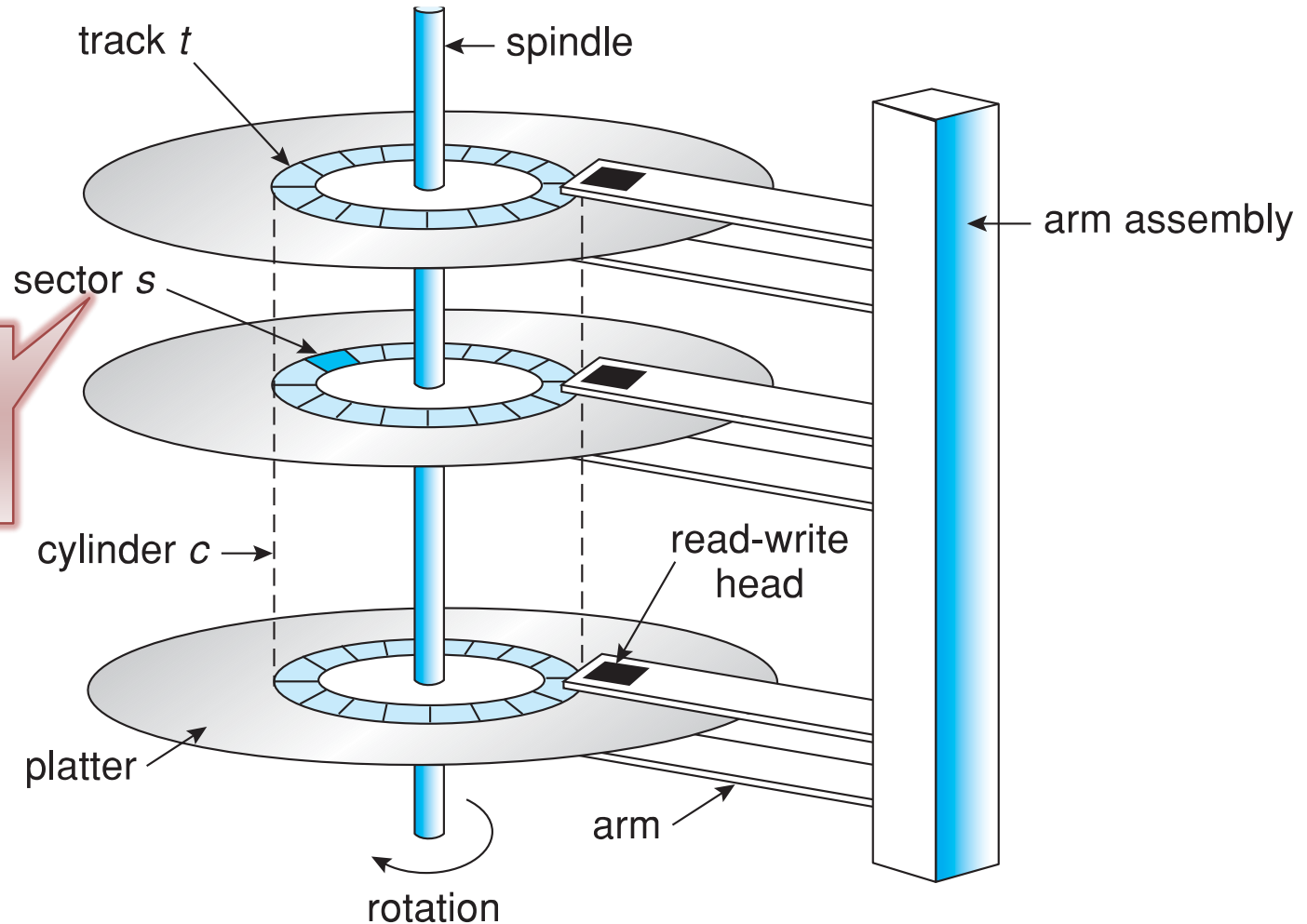
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Mass-Storage Structure

Moving-Head Disk Mechanism



The size of a sector is from 512B to 4KB

Disk Scheduling

- ▶ The disk I/O request specifies several pieces of information:
 - Whether this operation is input or output
 - What the disk address for the transfer is
 - What the memory address for the transfer is
 - What the number of sectors to be transferred is
- ▶ When there are multiple request pending, a good disk scheduling algorithm is required
 - Fairness: which request is the most urgent one
 - Performance: sequential access is preferred

Cylinders	1	2	3	4	5	6	7
Requests	5	7	2	6	4	1	3

Resort the requests?



Magnetic Disk Performance

- ▶ Access Latency = Average access time = average seek time + average rotation latency
 - For fastest disk $3\text{ms} + 2\text{ms} = 5\text{ms}$
 - For slow disk $9\text{ms} + 5.56\text{ms} = 14.56\text{ms}$
- ▶ Average I/O time = average access time + (amount to transfer / transfer rate) + controller overhead





System Protection and Security

Principles of Protection

- ▶ Principle of Least Privilege
 - Programs, users and systems should be given just enough privileges to perform their tasks
 - Limits damage if entity has a bug or gets abused
- ▶ Principle of Need-to-Know
 - At any time, a process should be able to access only those resources that it currently requires to complete its task

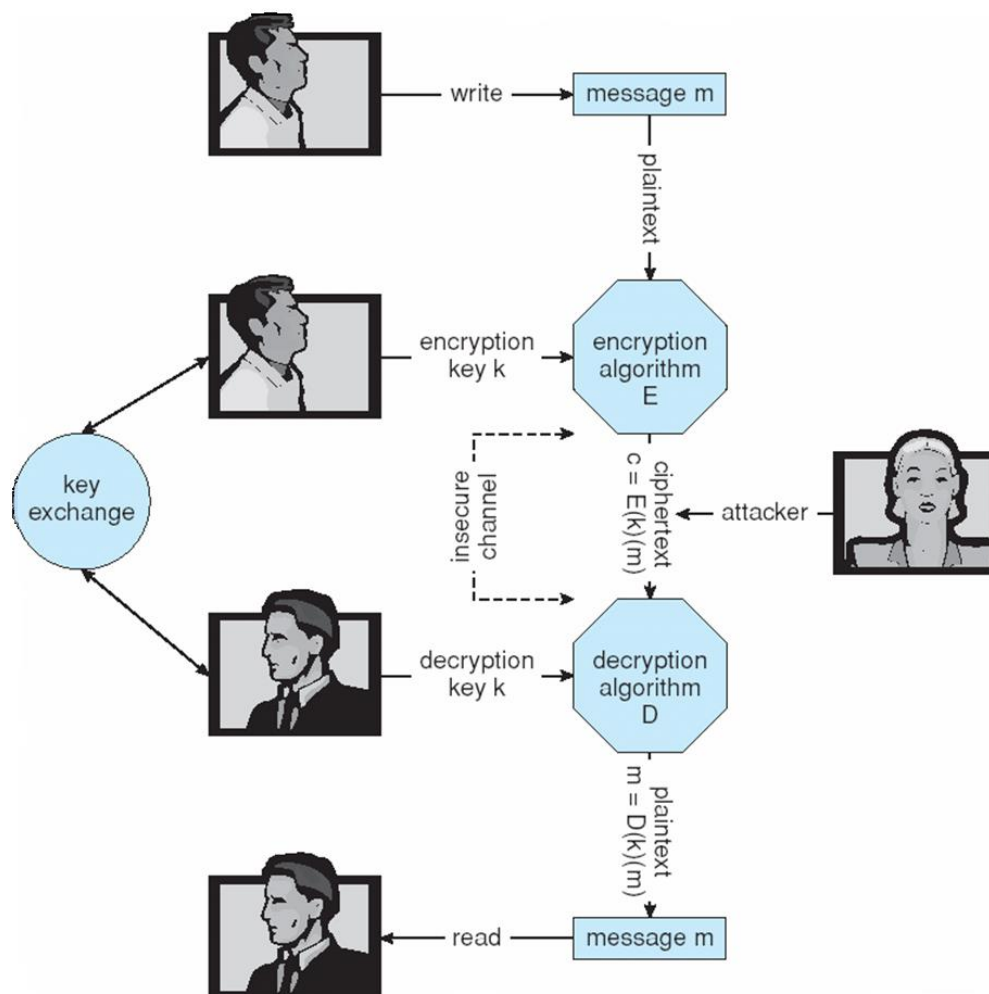


Security Violation Categories

- ▶ Breach of confidentiality
 - Unauthorized reading of data
- ▶ Breach of integrity
 - Unauthorized modification of data
- ▶ Breach of availability
 - Unauthorized destruction of data
- ▶ Theft of service
 - Unauthorized use of resources
- ▶ Denial of service (DOS)
 - Prevention of legitimate use



Secure Communication over Insecure Medium



Scenario of Asymmetric Encryption

