Operating System Concepts

Che-Wei Chang

chewei@mail.cgu.edu.tw

Department of Computer Science and Information Engineering, Chang Gung University

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

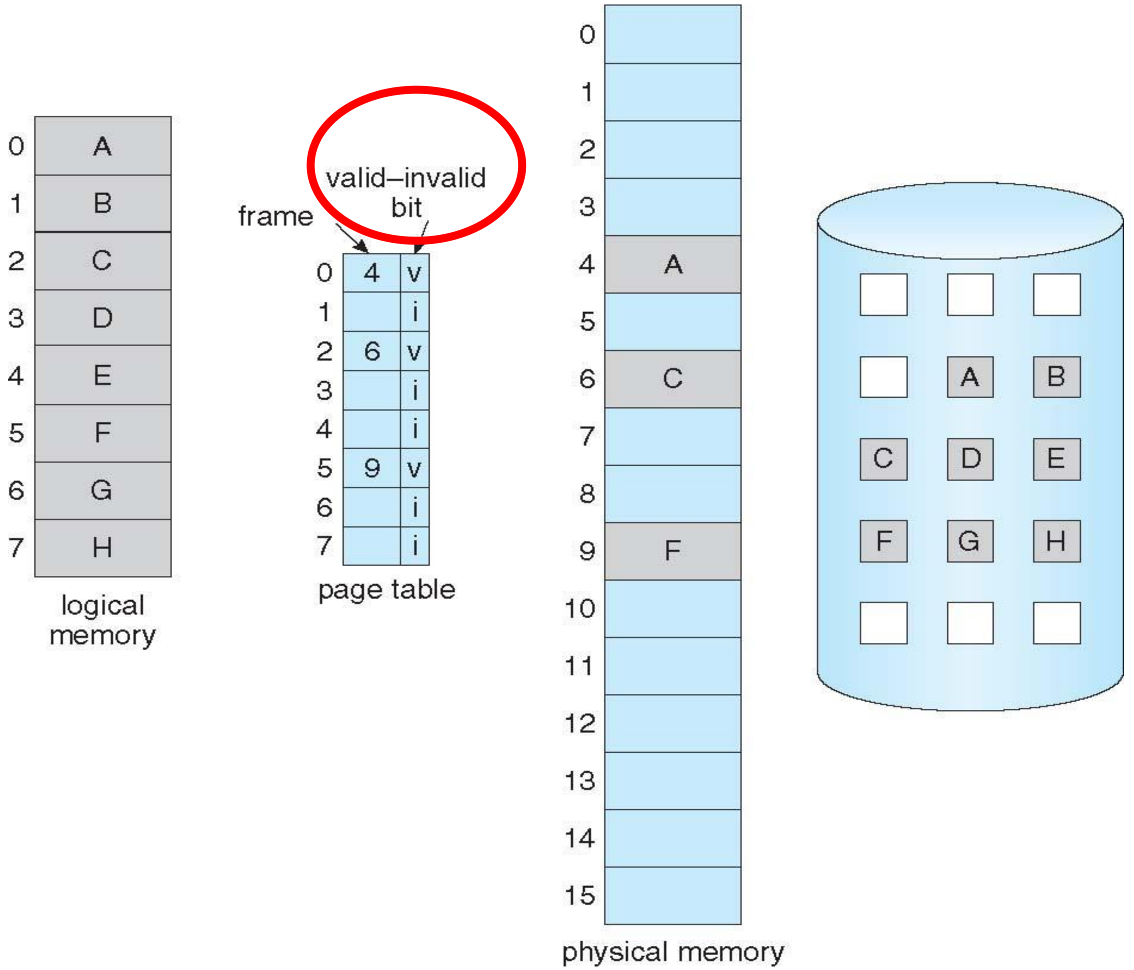
- Process image may reside on the backing store
  - Rather than swap in the entire process image into memory Lazy Swapper only swaps in a page when it is needed
- A mechanism is required to recover from the missing of non-resident referenced pages
  - A Page Fault occurs when a process references a non-memory-resident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

Hardware Support for Demand Paging

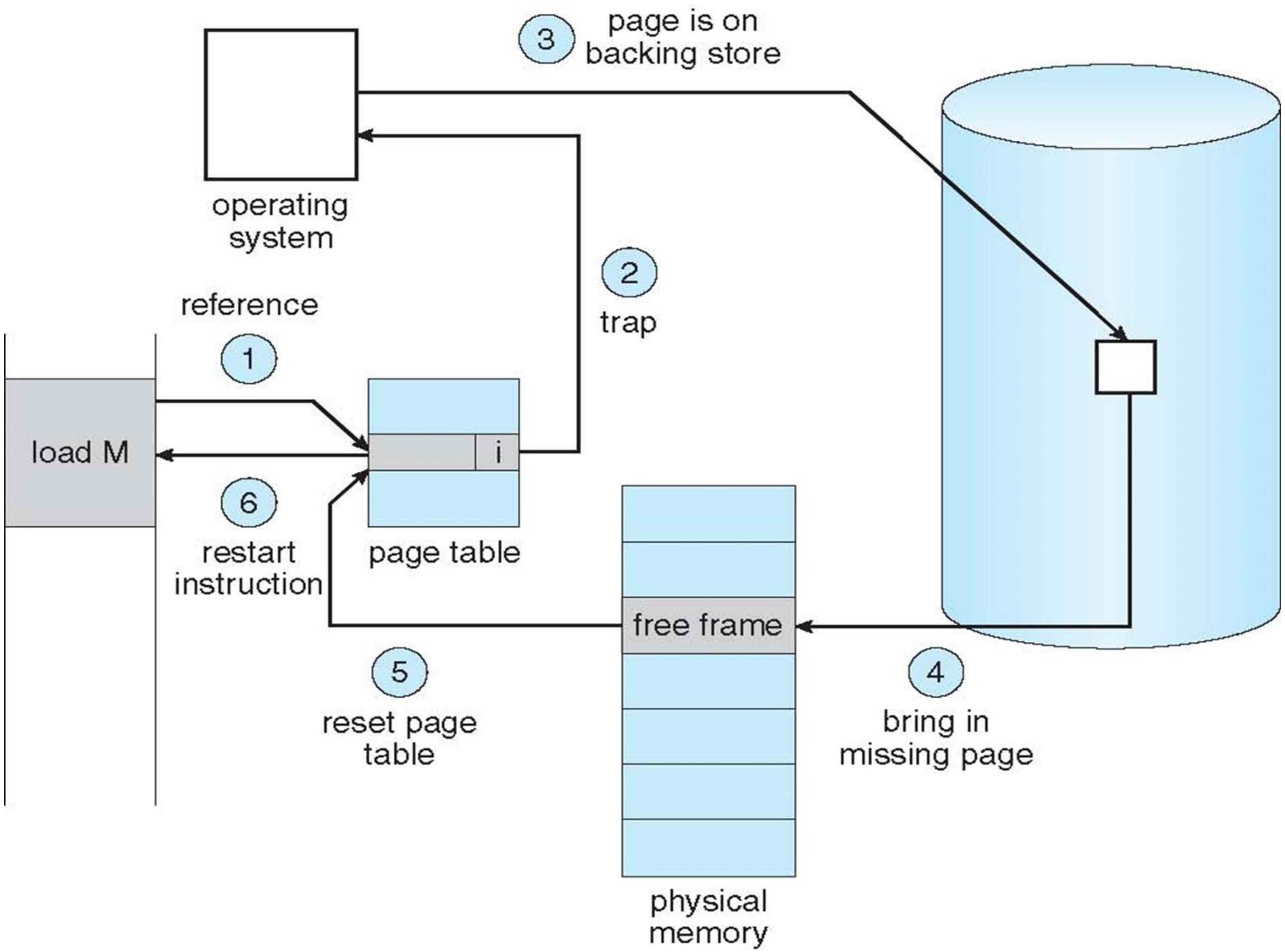
- New bits in the page table
  - To indicate that a page is now in memory or not

- 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 $0 \le p \le 1$
  - if $p = 0$ no page faults
  - if $p = 1$, every reference is a fault

- Effective Access Time (EAT)

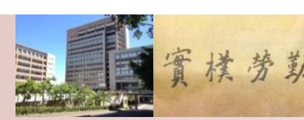
EAT = $(1 - p)$ x memory-access time
+ p (page fault overhead
+ swap page out
+ swap page in
+ restart overhead)

Department of Computer Science and Information Engineering, Chang Gung University

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!

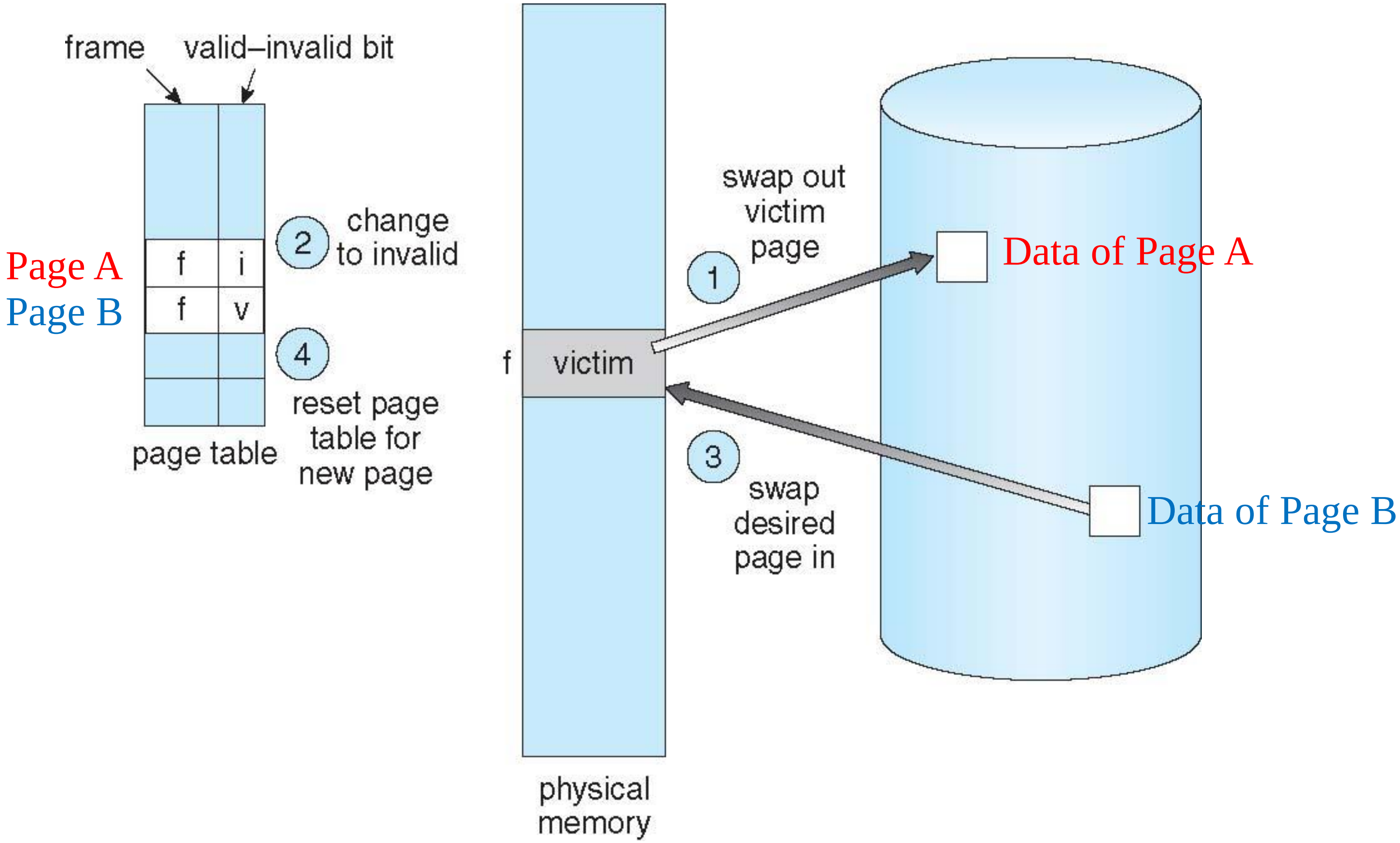
Page Replacement

- 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

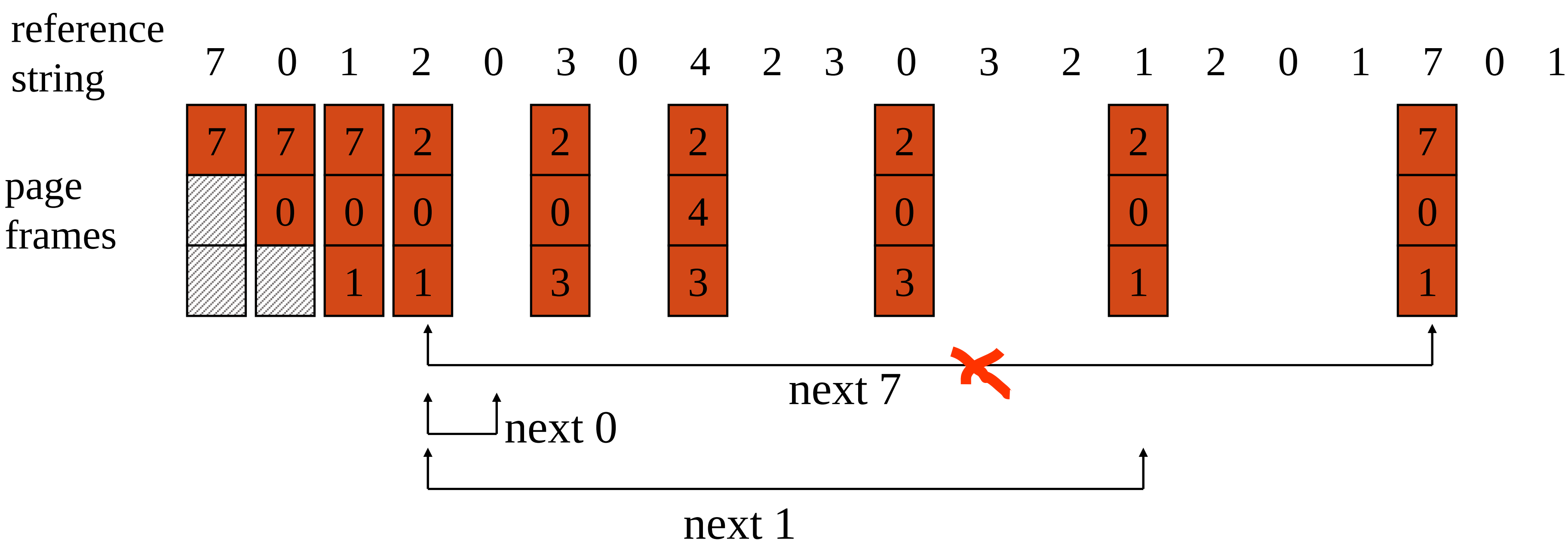
Page Replacement — FIFO Algorithm

- 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	7	7	7	2		2	2	4	4	4	0			0	0			7	7	7
		0	0	0		3	3	3	2	2	2			1	1			1	0	0
			1	1		1	0	0	0	3	3			3	2			2	2	1
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

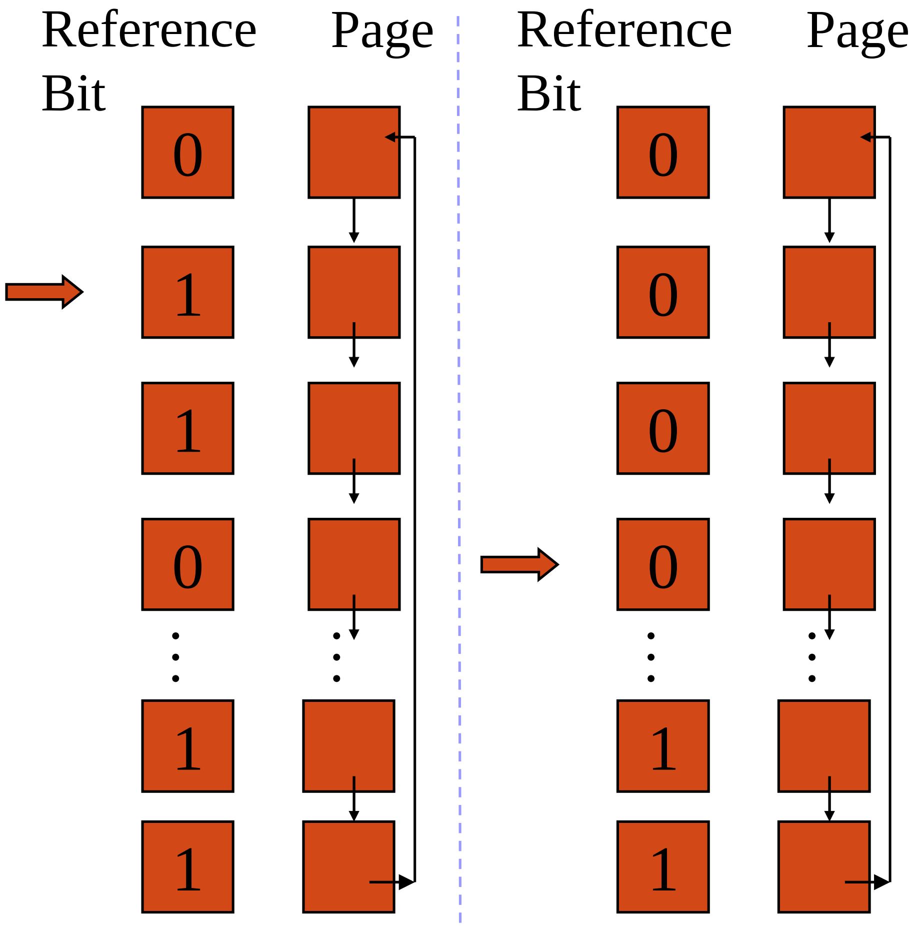
- Least-Recently-Used Algorithm (LRU)
  - We don’t have knowledge about the future
  - Thus, we use the history of page referencing in the past to predict the future

➔ 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	7	2		2		4	4	4	0			1		1		1		
		0	0	0		0		0	0	3	3			3		0		0		
			1	1		3		3	2	2	2			2		2		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

Low Priority

- (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

High Priority

- We replace the first page encountered in the lowest nonempty class

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 rated, 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

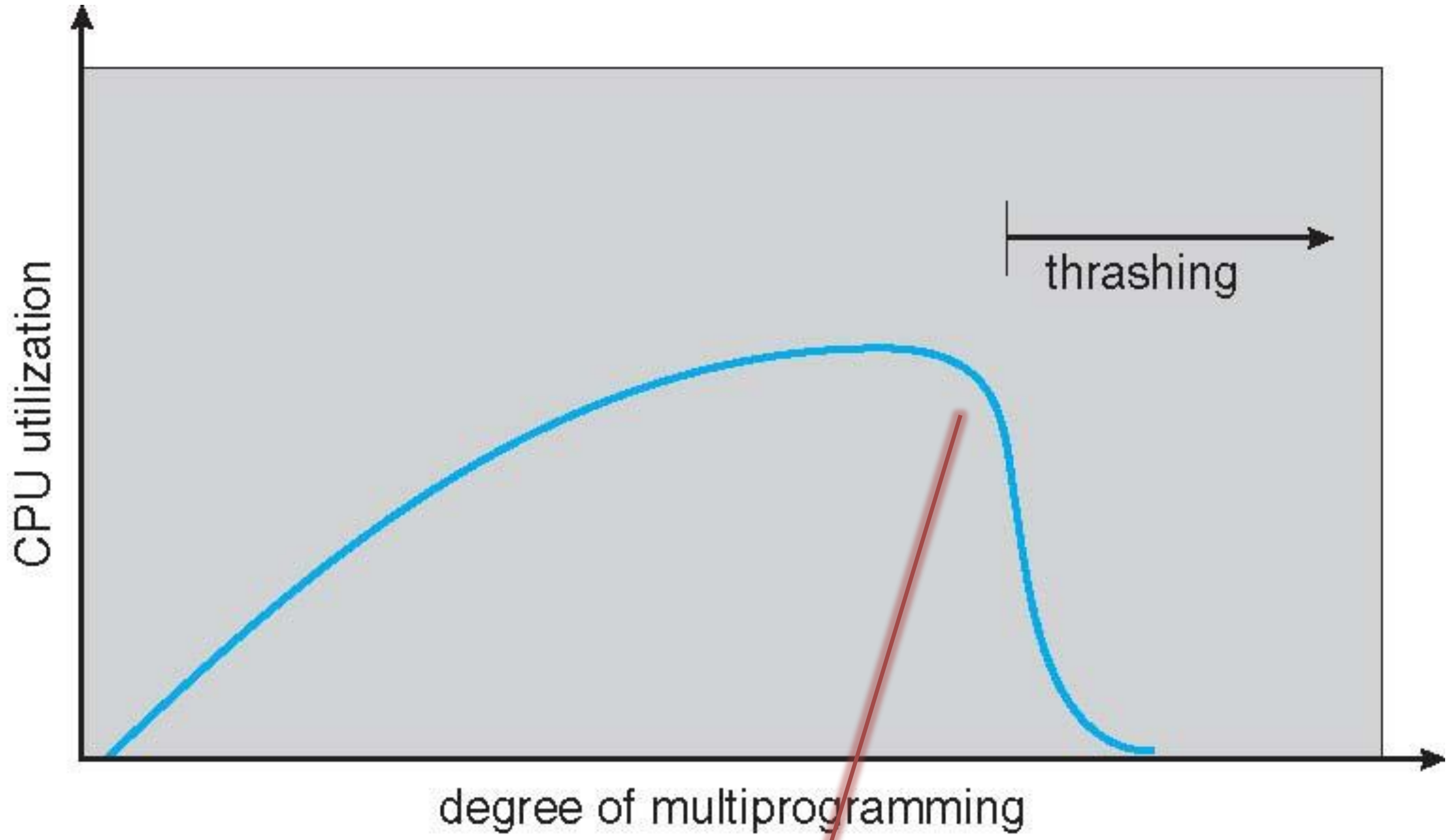
Non-Uniform Memory Access

- 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

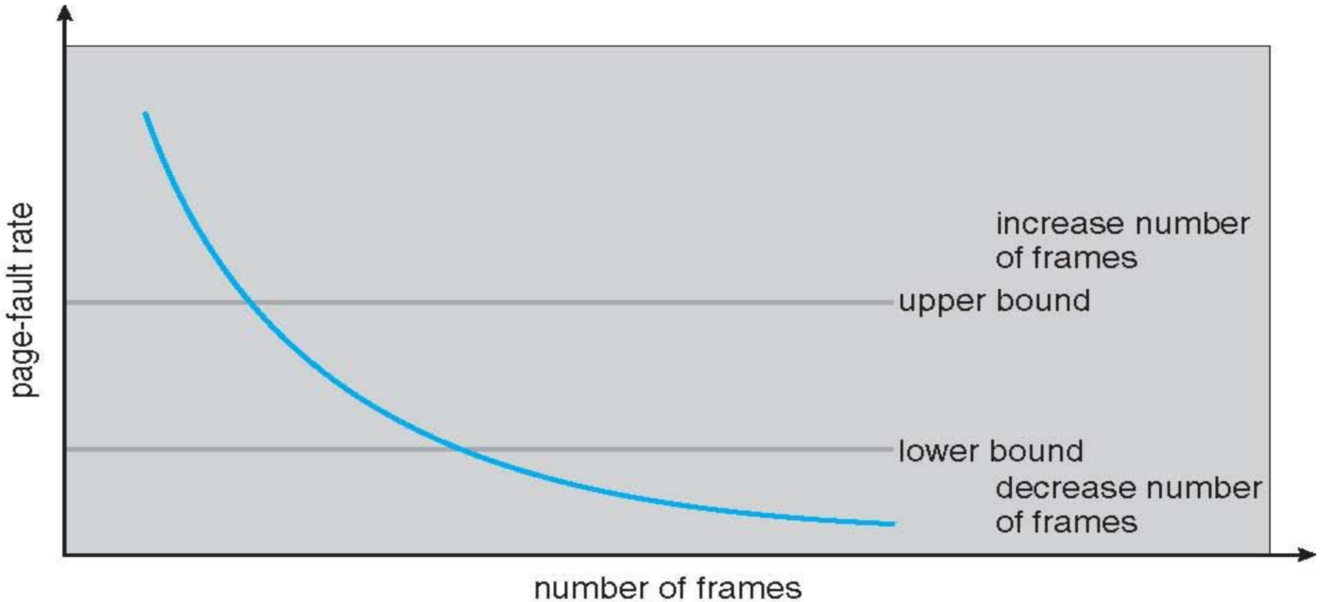
Thrashing (2/2)



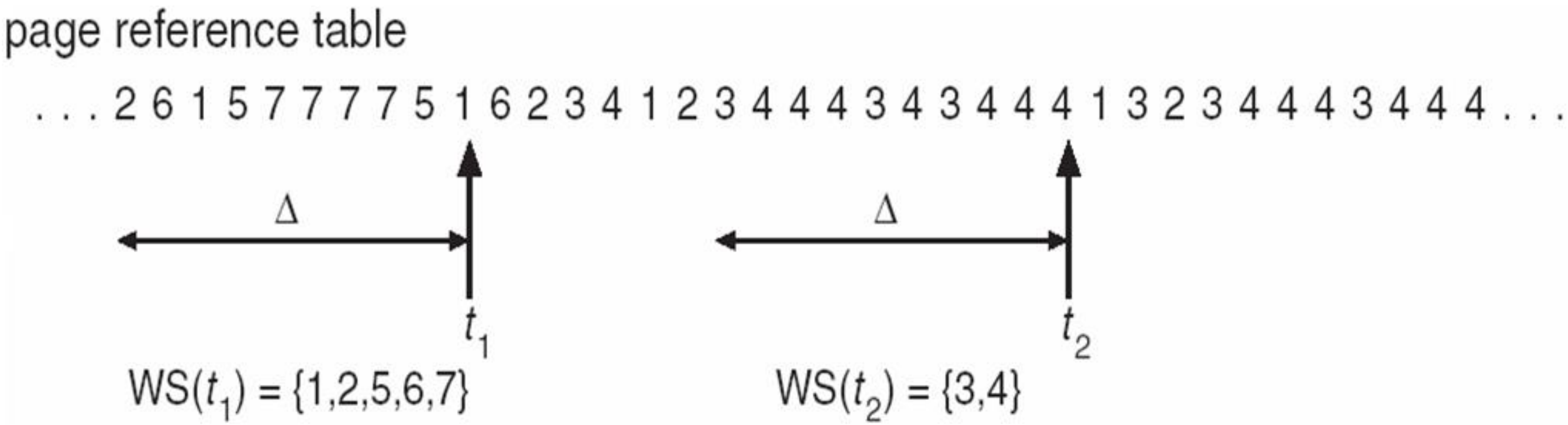
Be careful of the page fault rate

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)

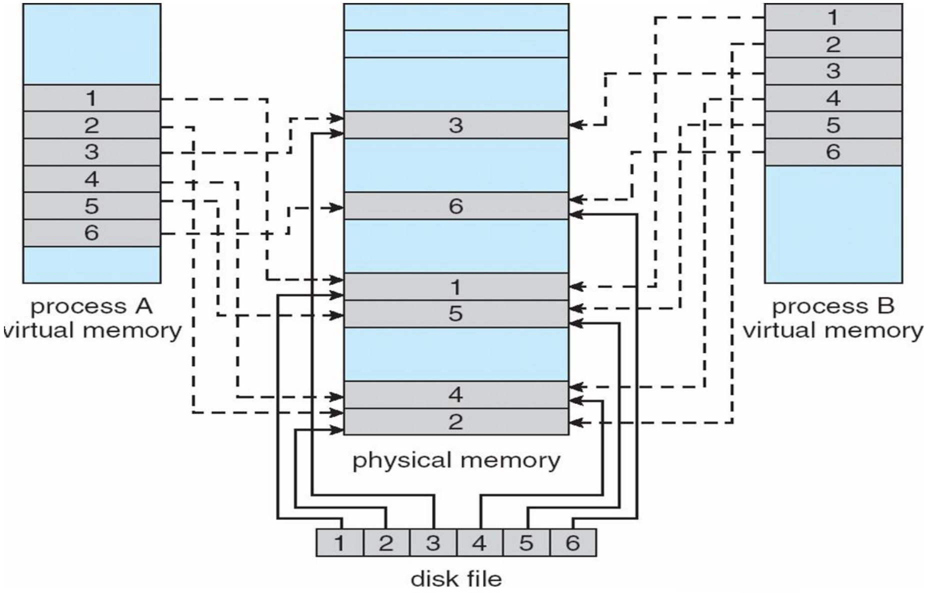


Working-Set Model (2/2)

- $\Delta \equiv$ 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
- $D = \Sigma\, WSS_i \equiv$ total demand frames
  - Approximation of locality
- if $D >$ *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



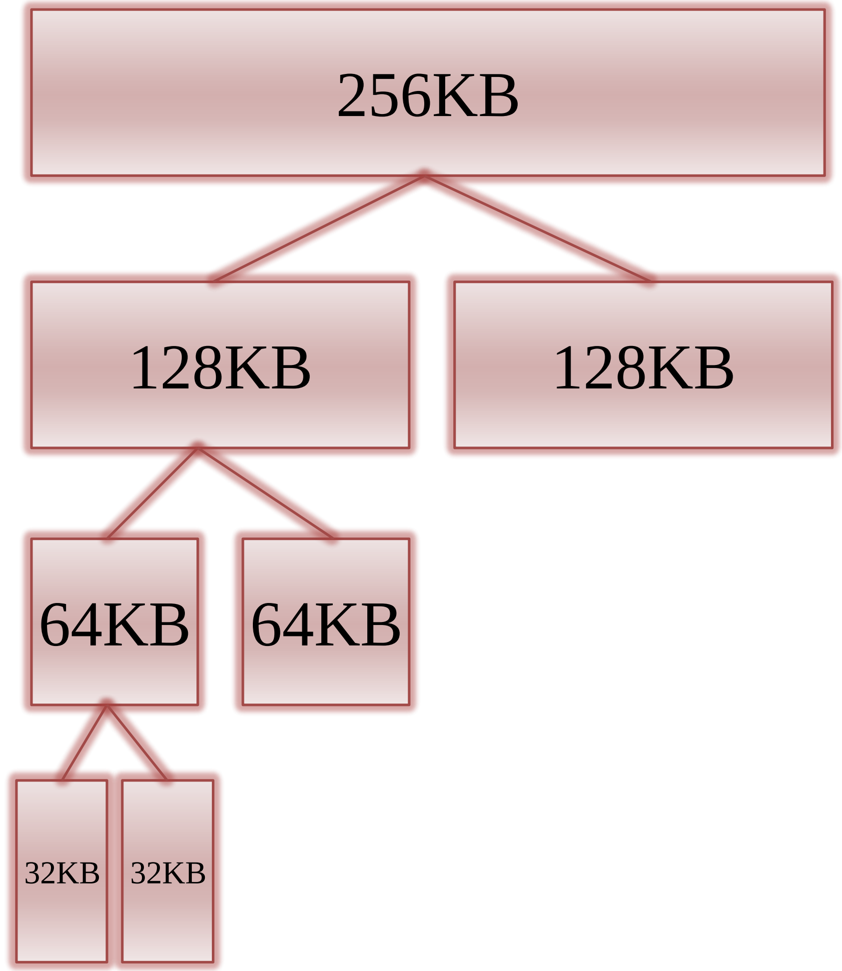
Department of Computer Science and Information Engineering, Chang Gung University

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

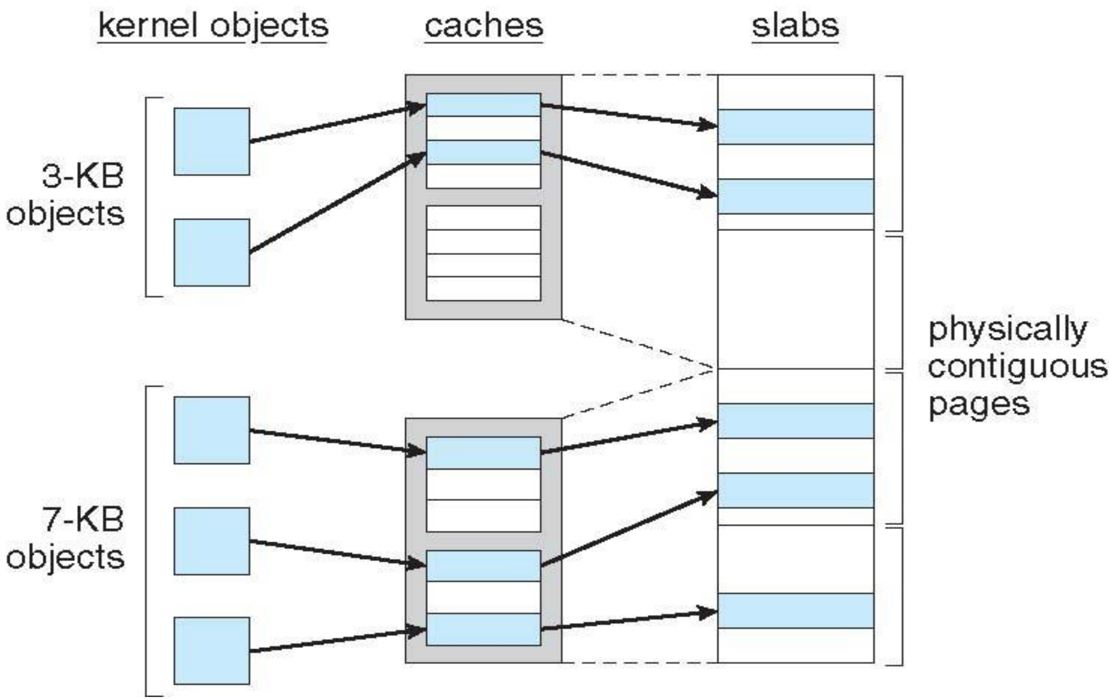
Kernel Memory Allocation (1/2)

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



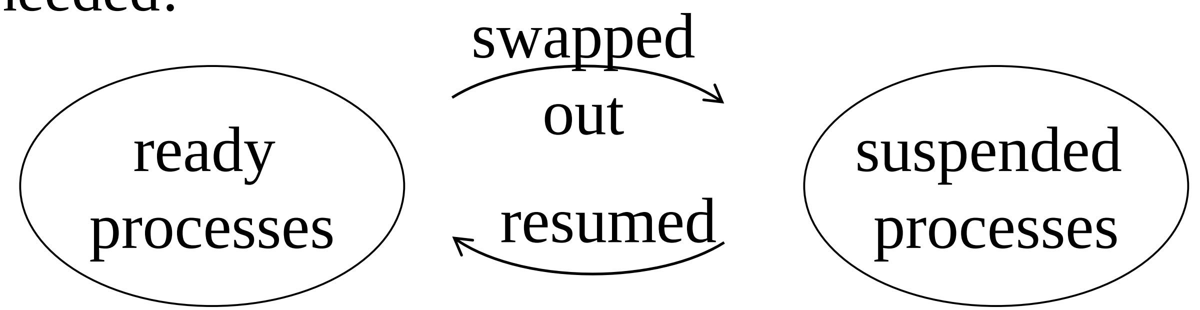
Kernel Memory Allocation (2/2)

- 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

Page Size

small ⟵ | p | d | ⟶ large

2^{12} (4KB) to 2^{22} (4MB)

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
- TLB Reach = (TLB Size) X (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

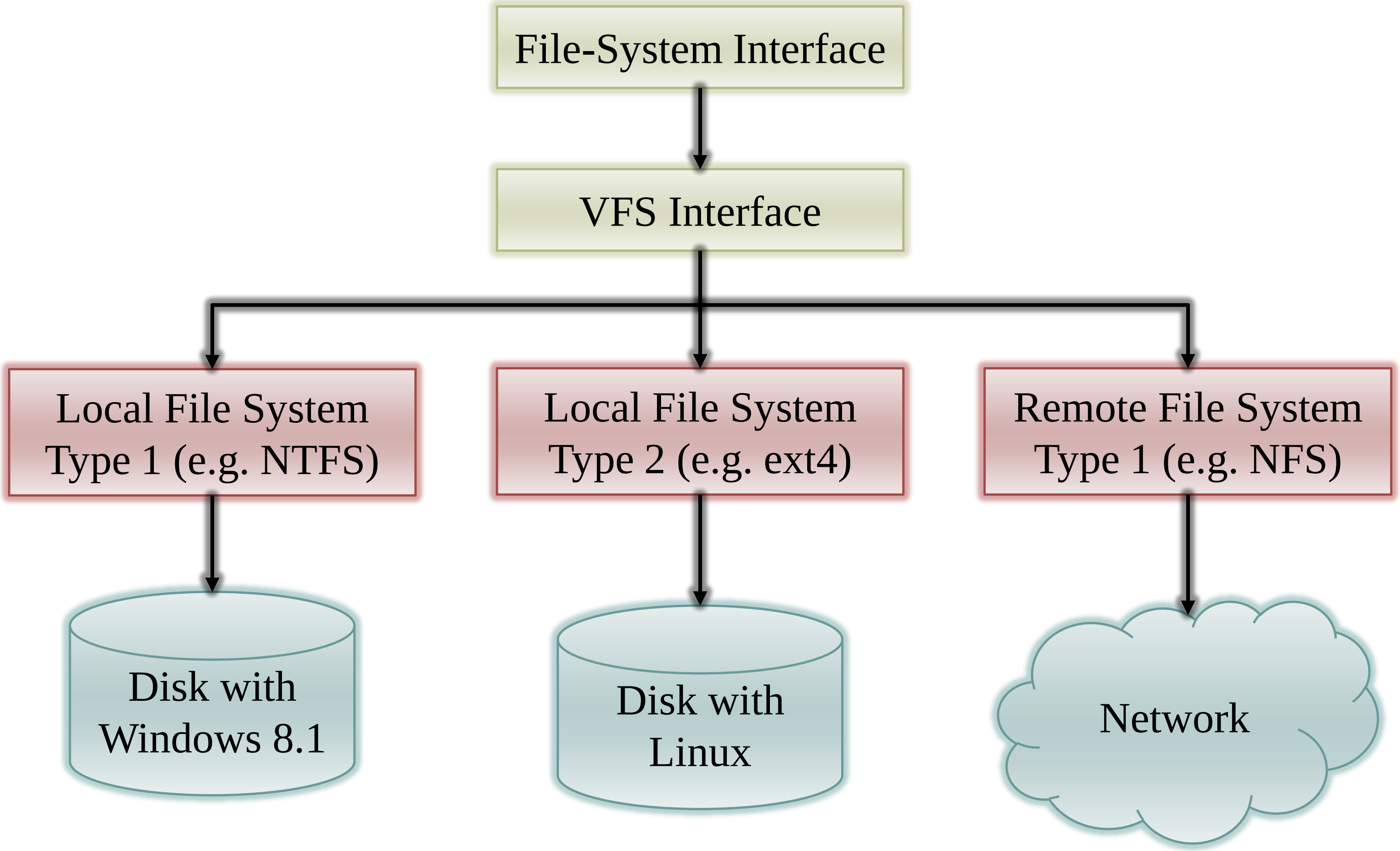
File Operations

- 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



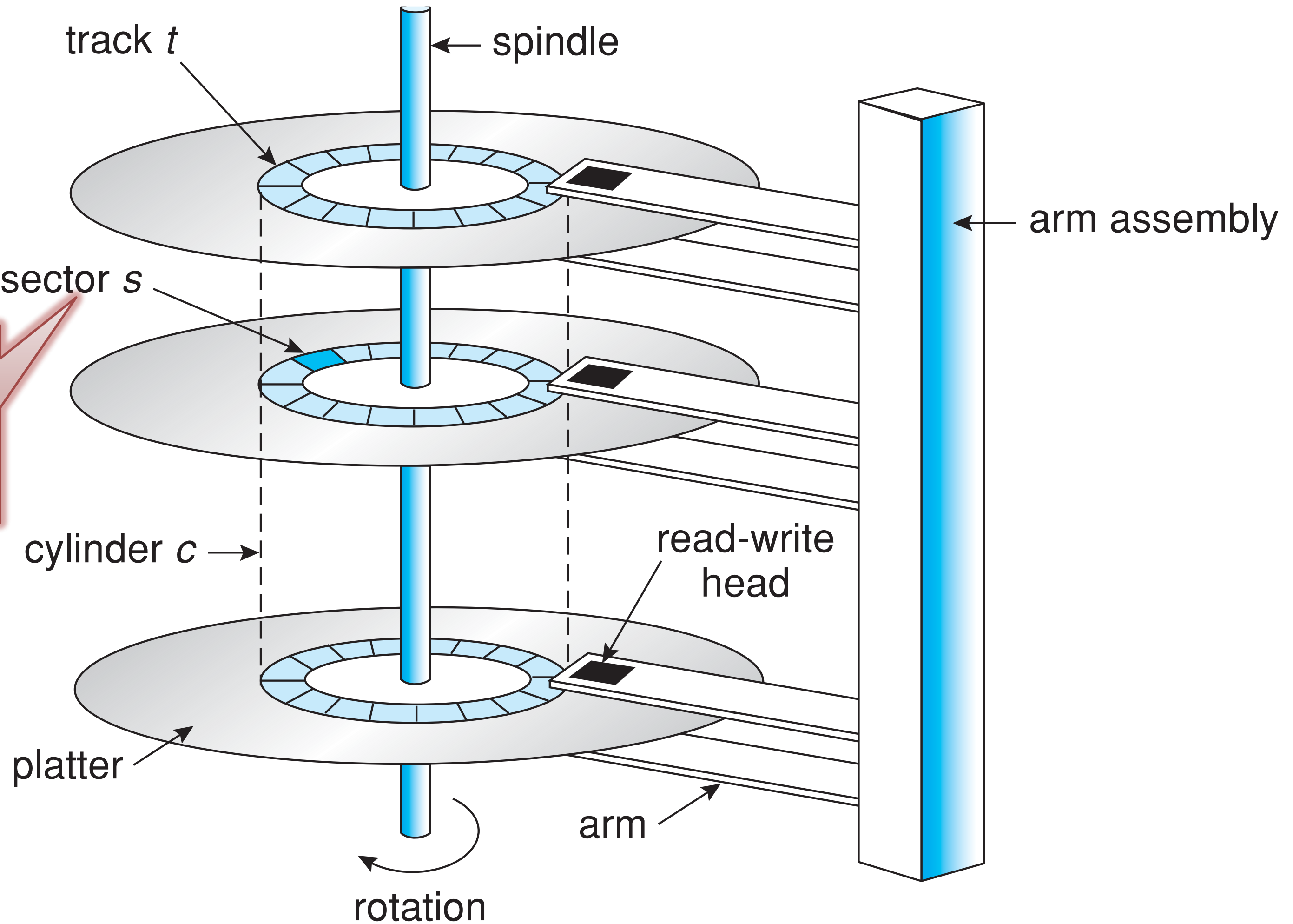
Virtual File System

- 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

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 3ms + 2ms = 5ms
  - For slow disk 9ms + 5.56ms = 14.56ms
- Average I/O time = average access time + (amount to transfer / transfer rate) + controller overhead

System Protection and Security

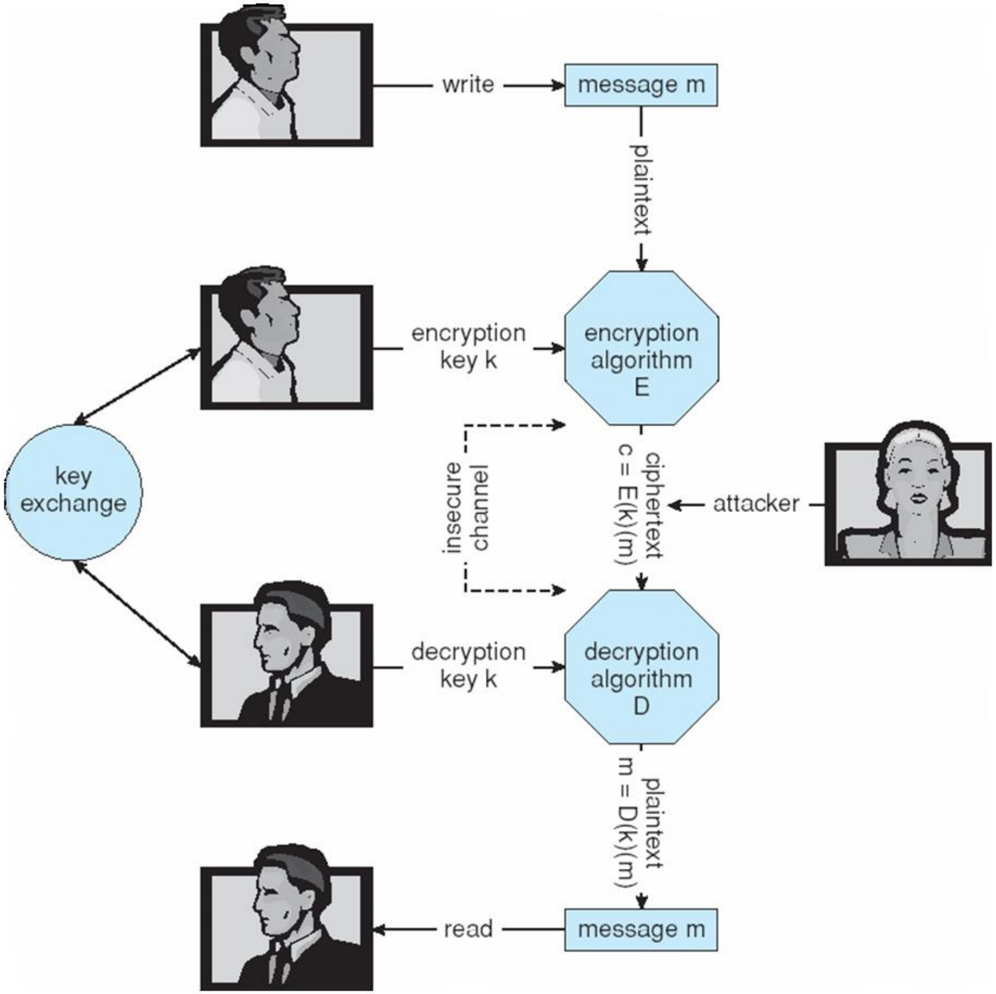
Principles of Protection

- 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



實樸勞勤

Scenario of Asymmetric Encryption