Operating System Concepts

Che-Wei Chang
chewei@mail.cgu.edu.tw
Department of Computer Science and Information Engineering, Chang Gung University

Contents

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

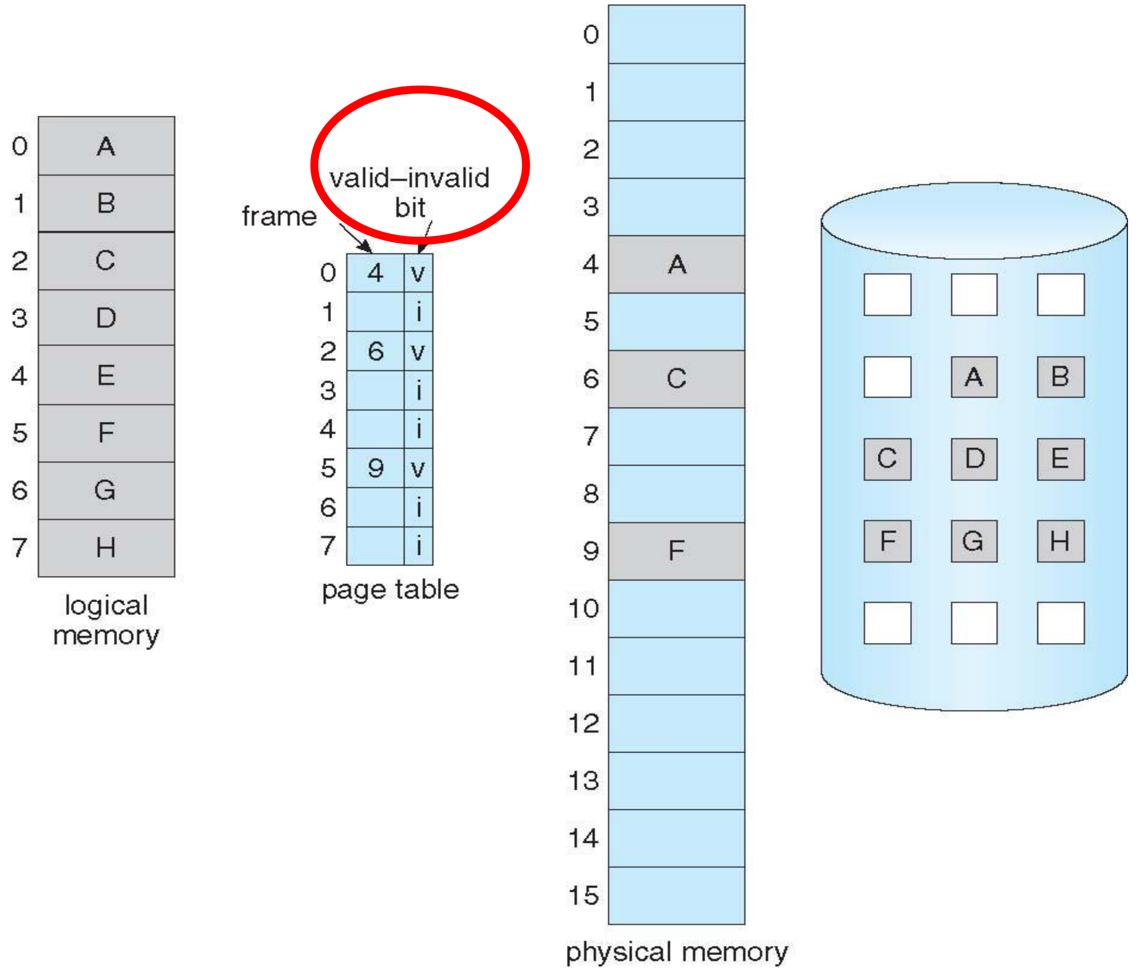
- Process image may reside on the backing store
  - Rather than swap in the entire process image into memory Lazy Swapper only swaps in a page when it is needed
- A mechanism is required to recover from the missing of non-resident referenced pages
  - A Page Fault occurs when a process references a non-memory-resident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

Hardware Support for Demand Paging

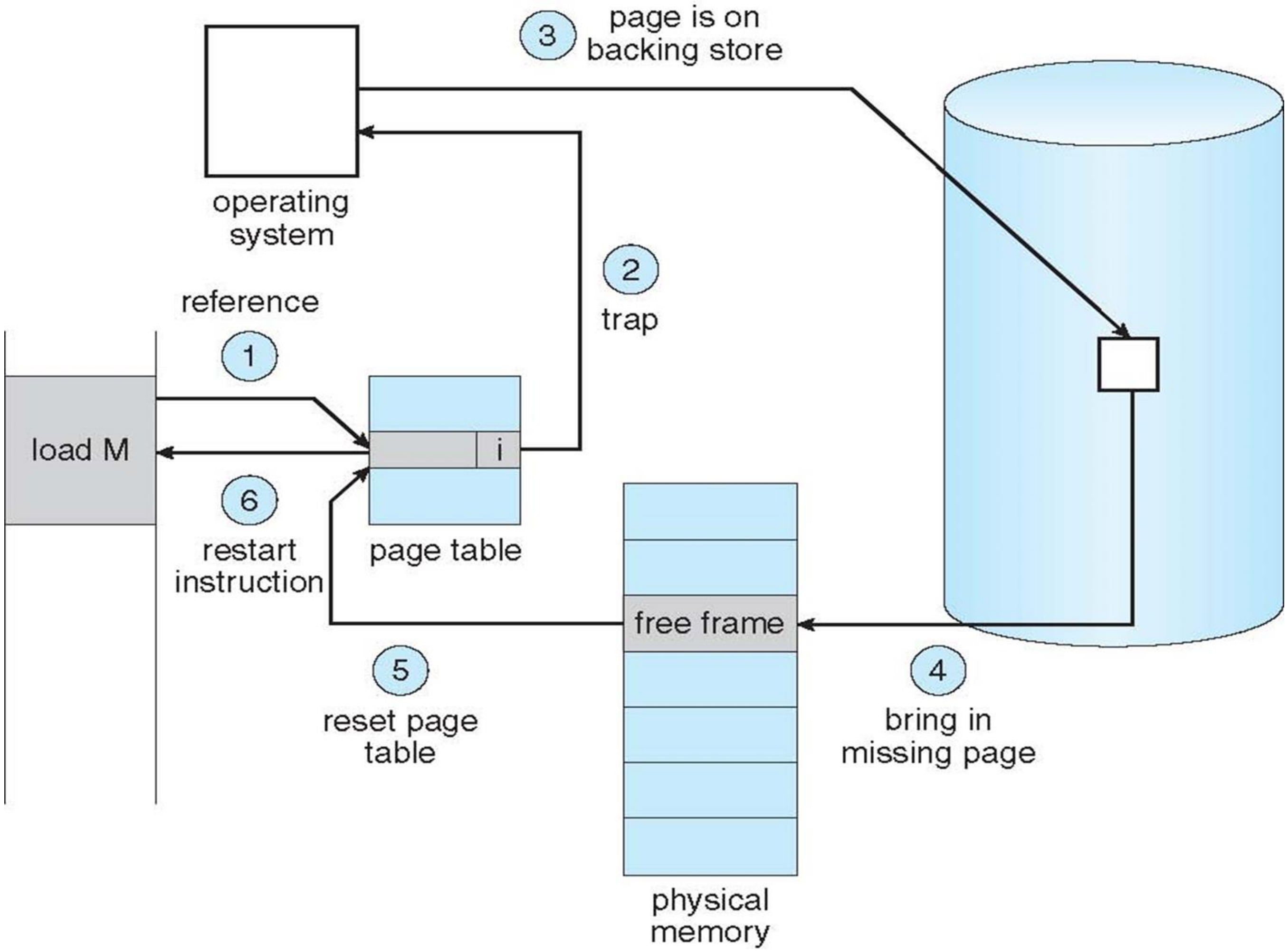
- New bits in the page table
  - To indicate that a page is now in memory or not

- 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)

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!

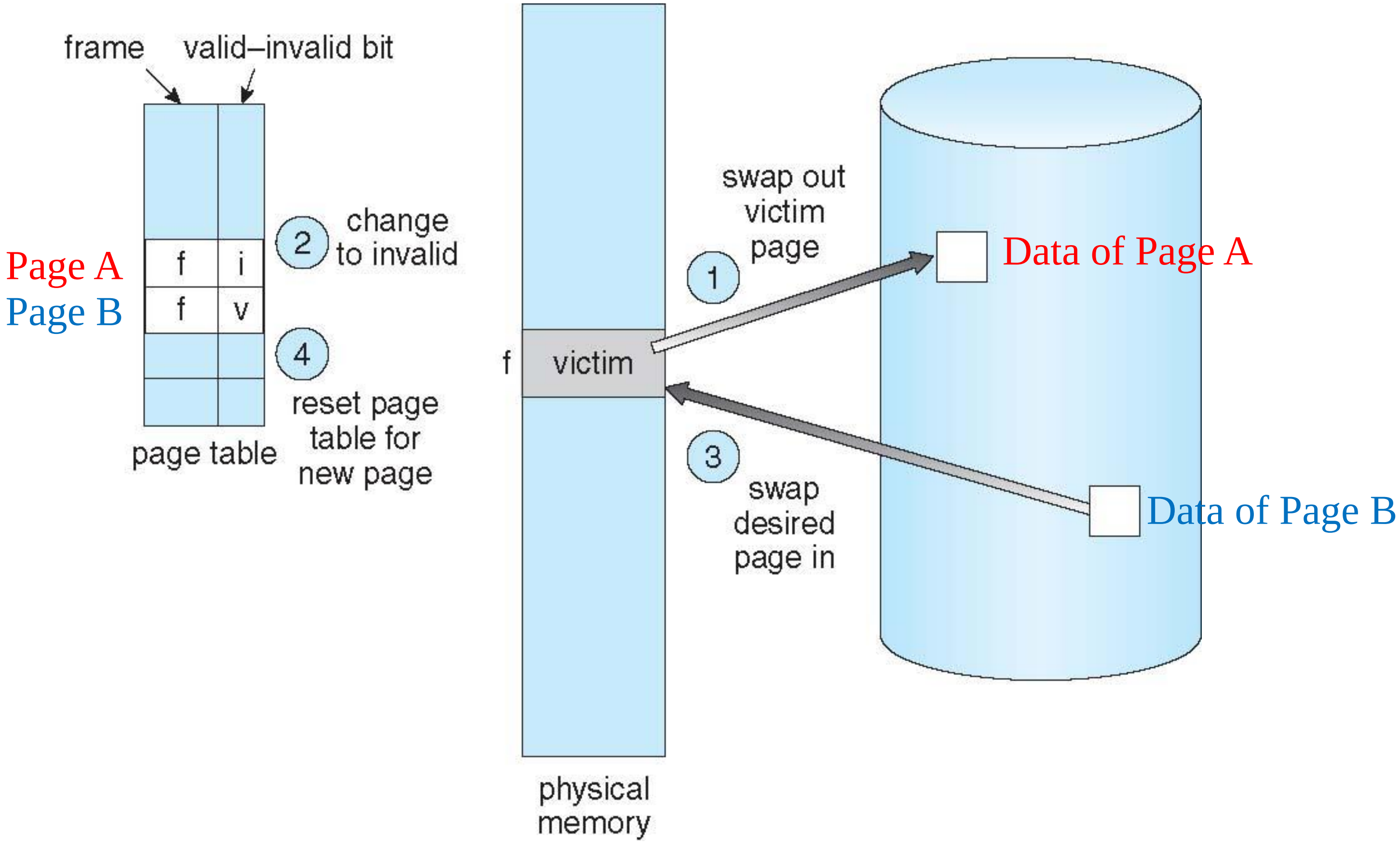
Page Replacement

- 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

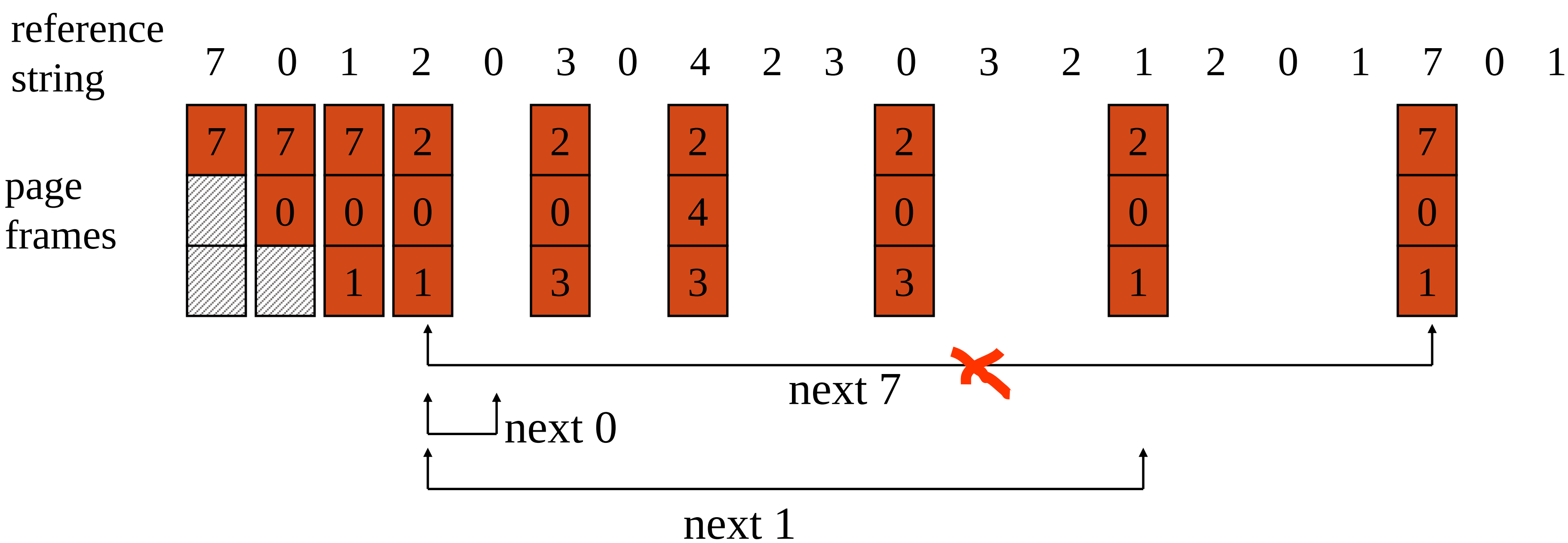
Page Replacement — FIFO Algorithm

- 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

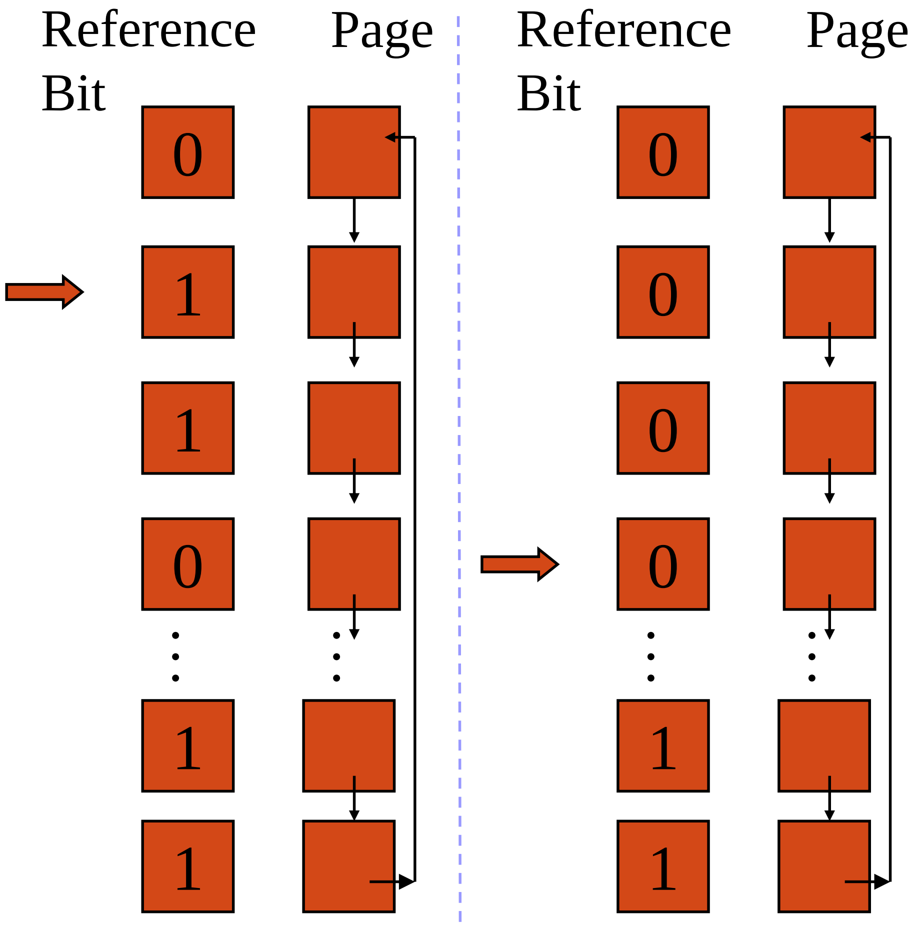
- Least-Recently-Used Algorithm (LRU)
  - We don’t have knowledge about the future
  - Thus, we use the history of page referencing in the past to predict the future

➔ 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
  - (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 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

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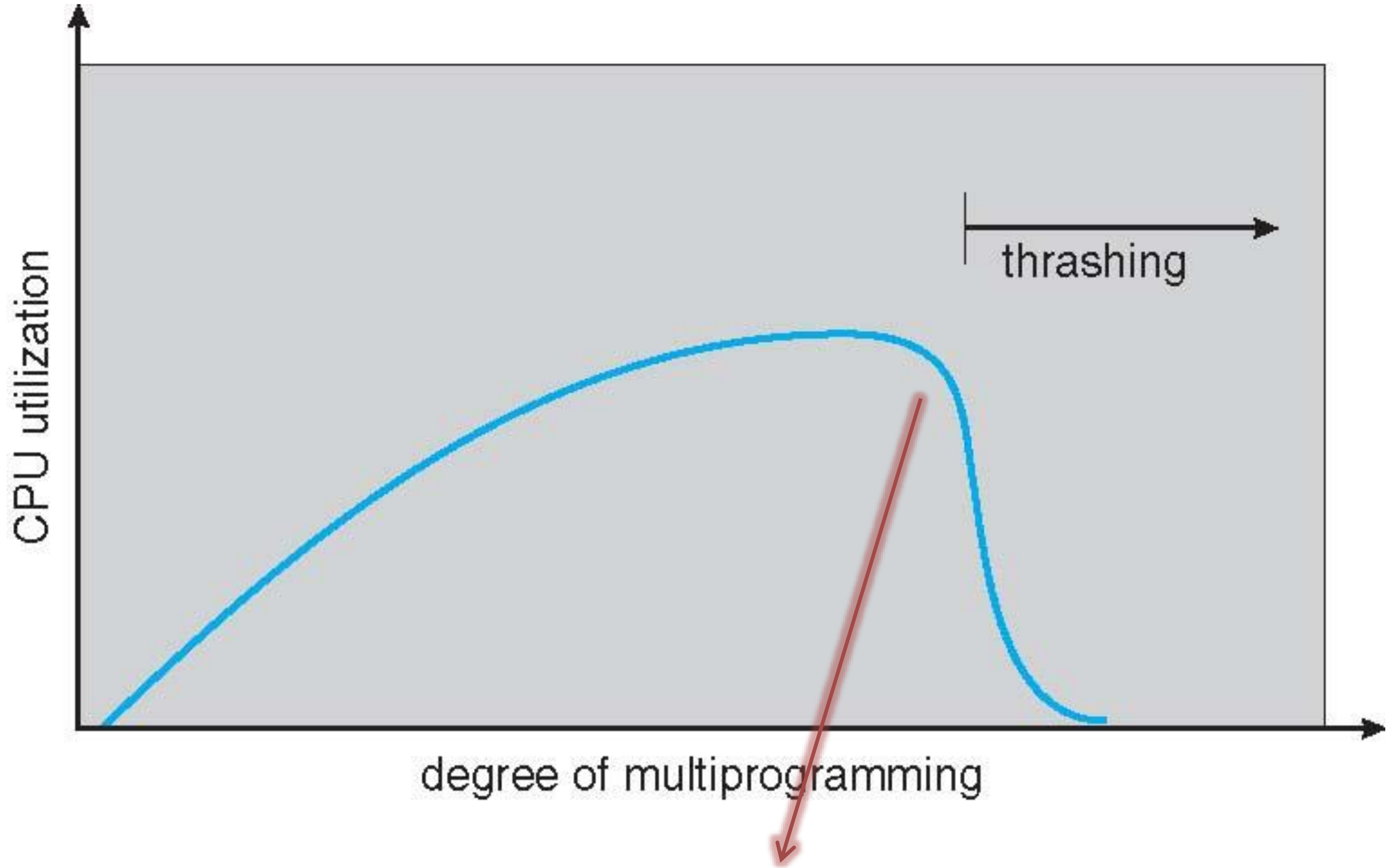
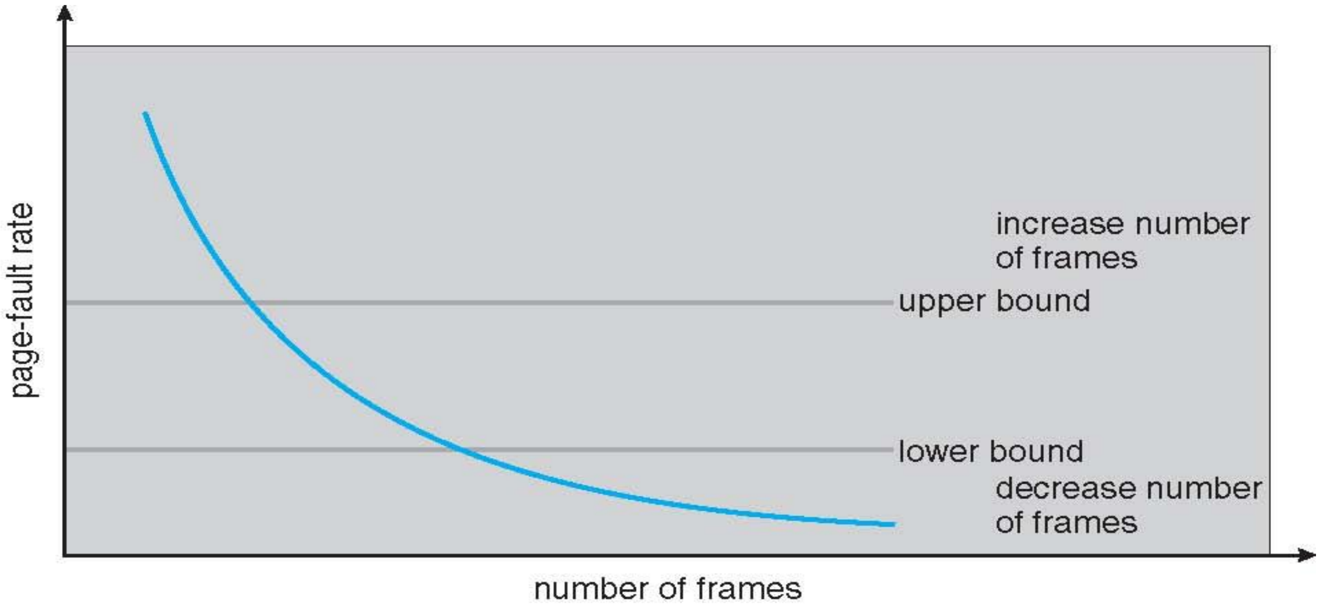
Thrashing (2/2)



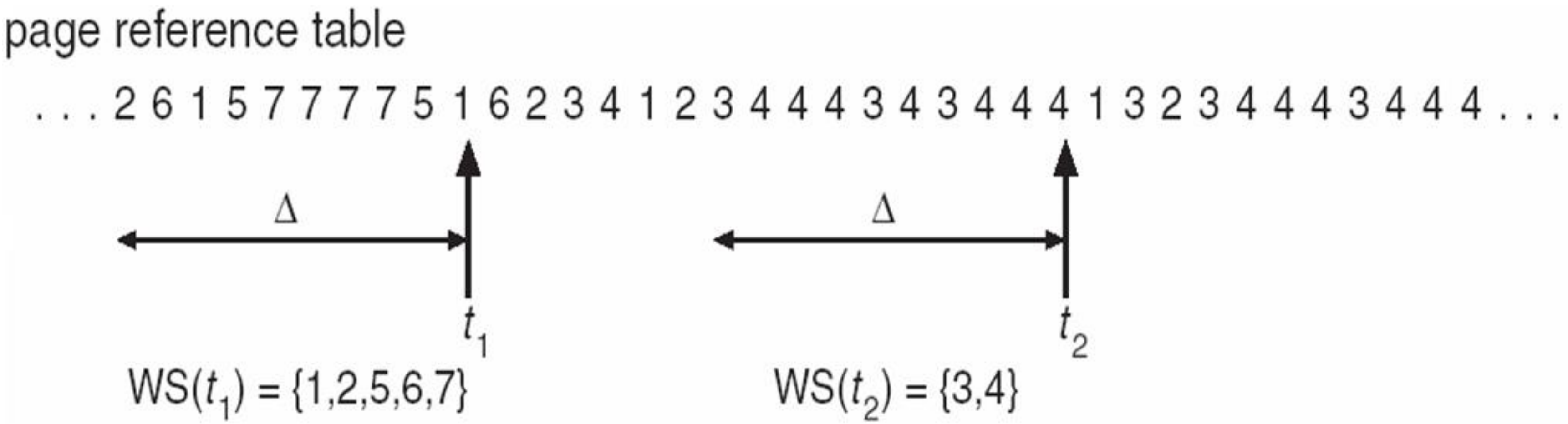
Be careful of the page fault rate

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)

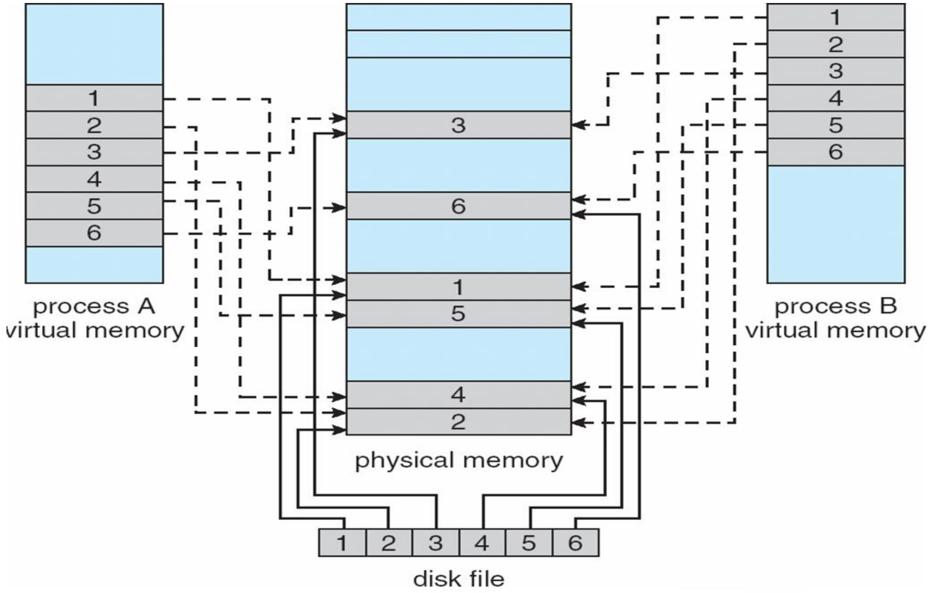


Working-Set Model (2/2)

- $\Delta \equiv$ 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* → 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



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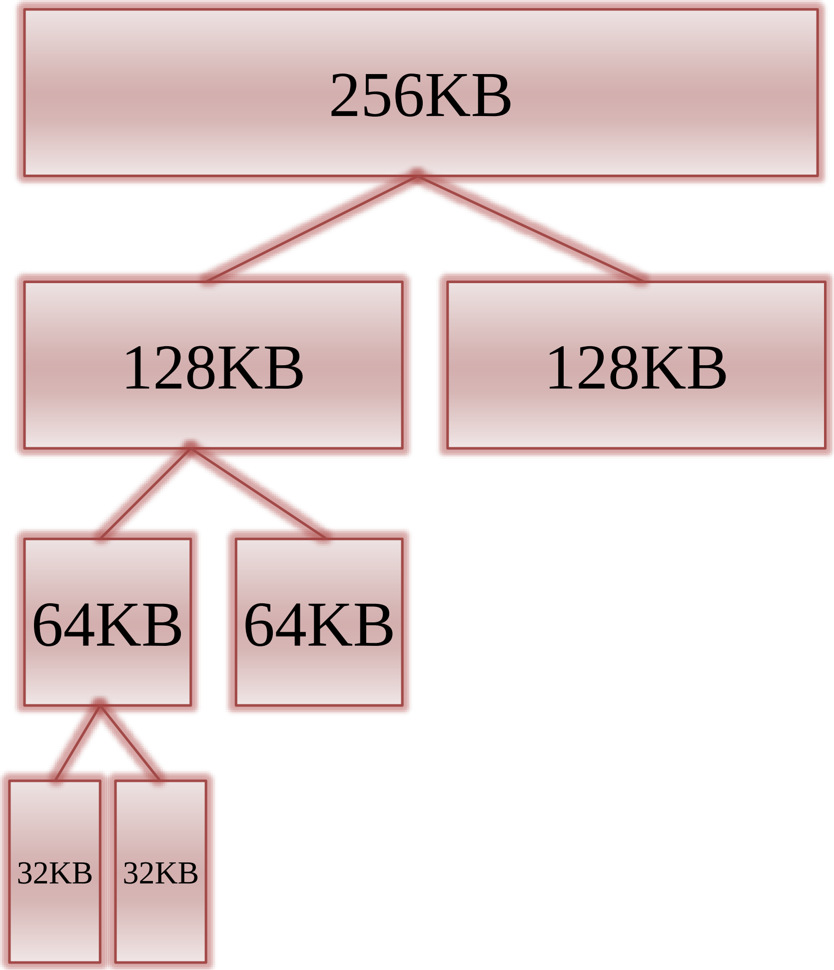
Memory-Mapped I/O

- 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

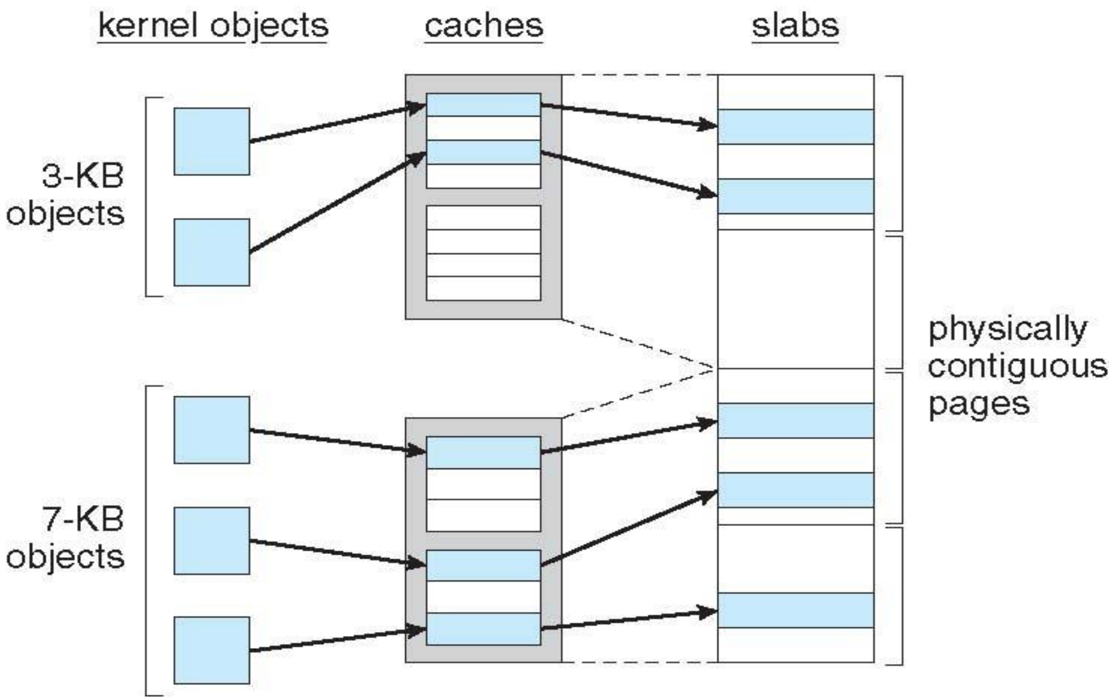
Kernel Memory Allocation (1/2)

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



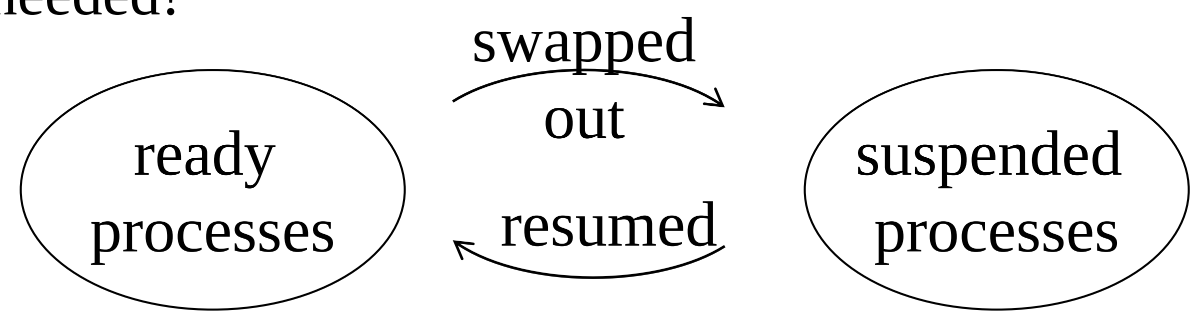
Kernel Memory Allocation (2/2)

- 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

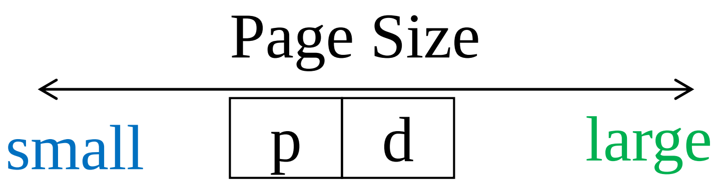
Pre-Paging Cost ⟷ Cost of Page Fault Services

Not every page in the working set will be used!

Other Considerations: Page Size

- Page Size

Better Resolution for Locality & Internal Fragmentation



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

Contents

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

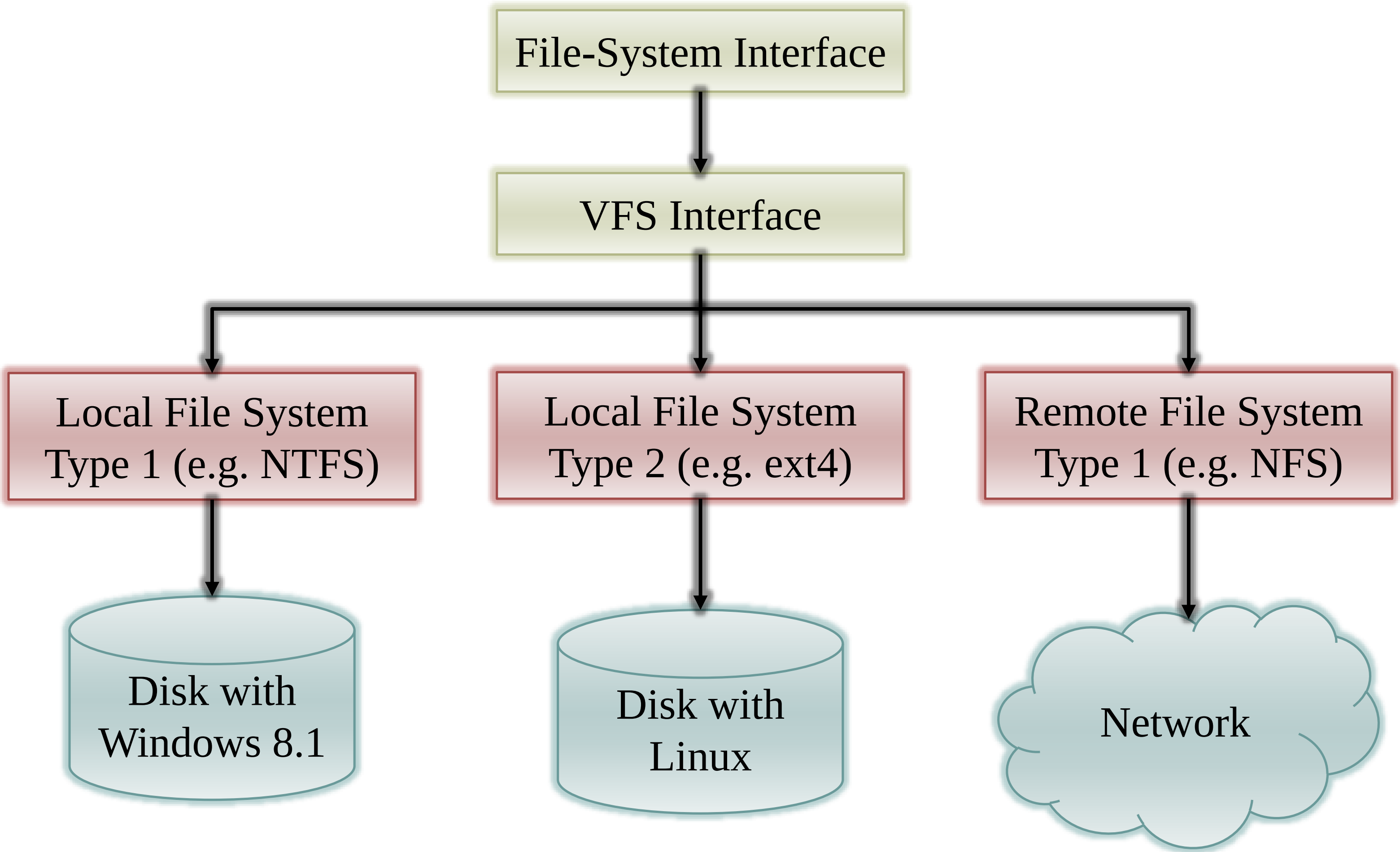
File Operations

- 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



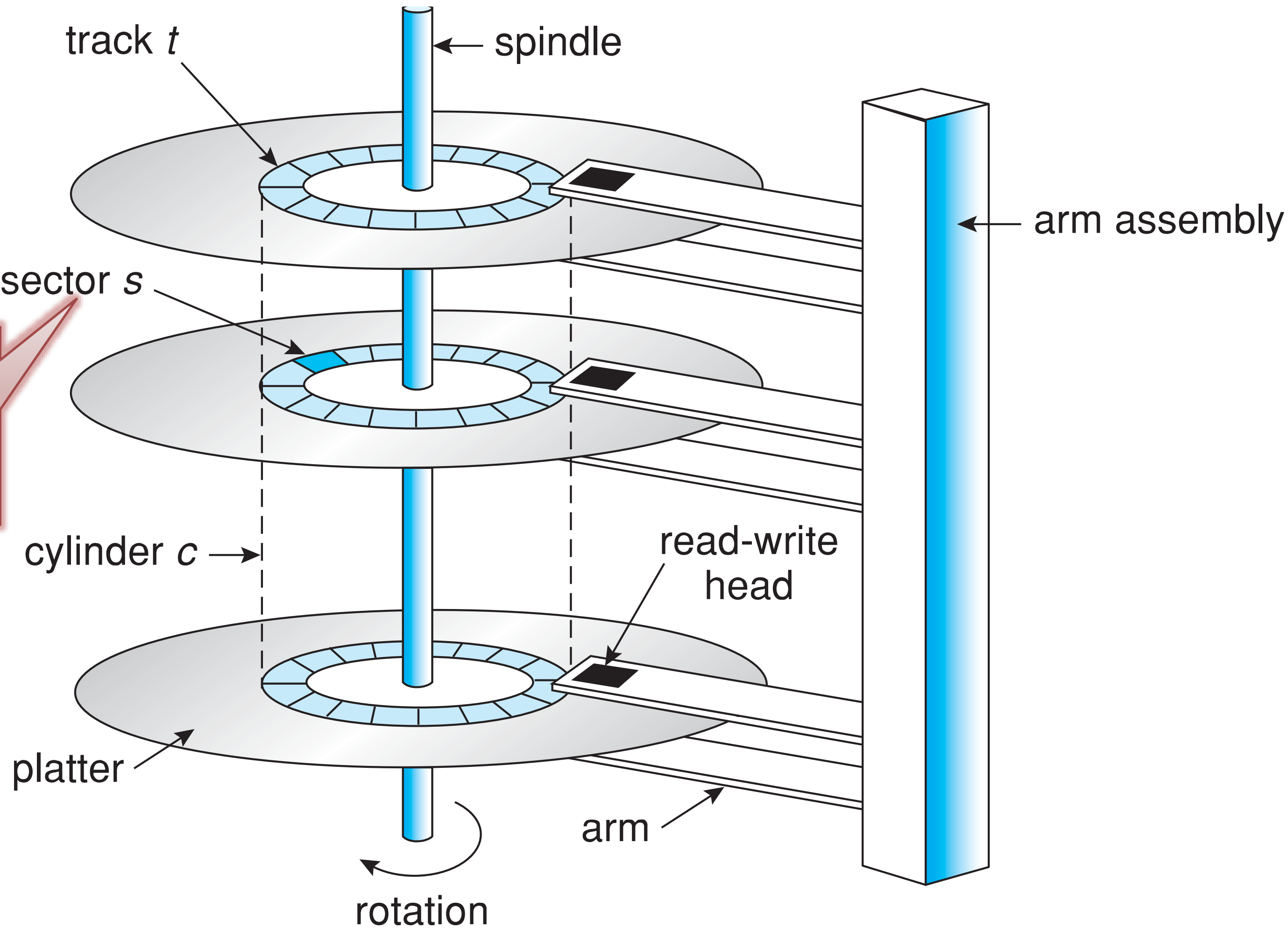
Virtual File System

- 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

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

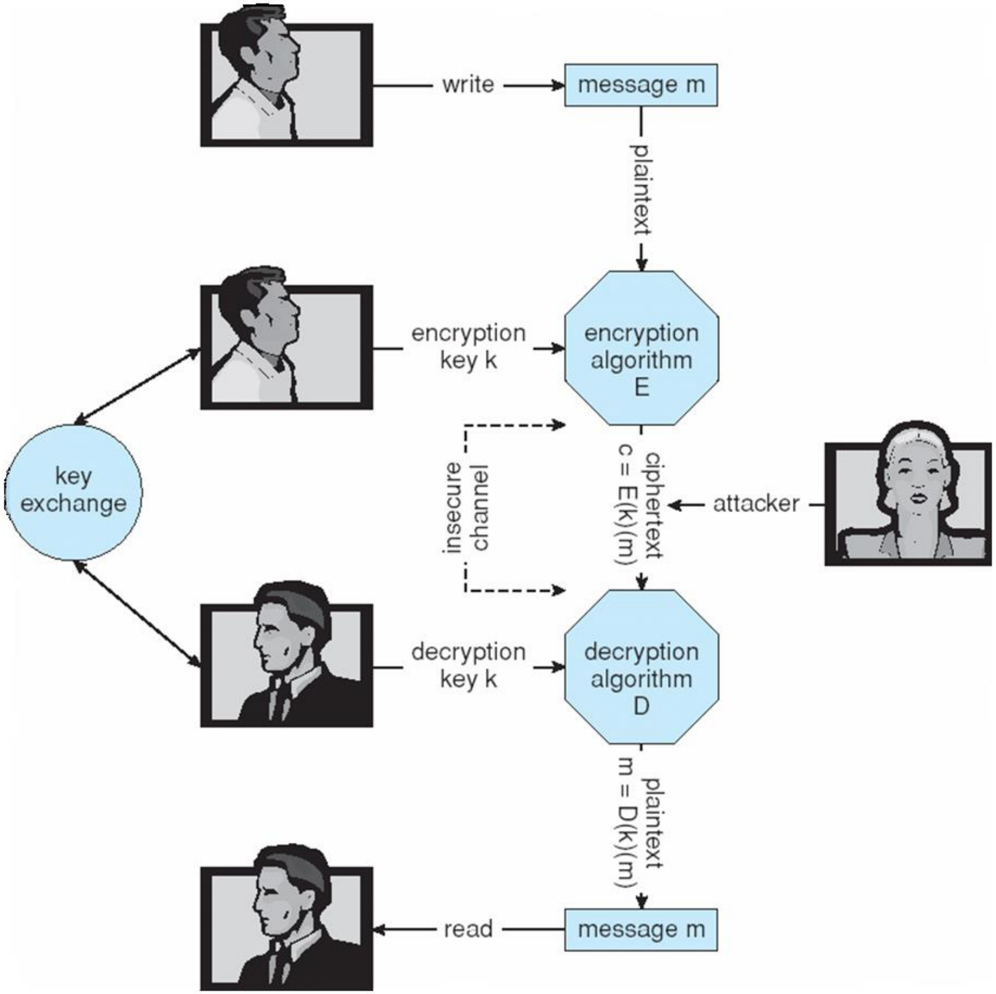
Principles of Protection

- 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



Scenario of Asymmetric Encryption