

# **Unit 4: Memory Management (8 Hrs.)**

## **4.1.1. Introduction to Memory Management**

Memory management is the process of coordinating and controlling the use of a computer's primary memory (RAM). Its goals include:

- **Efficiency:** Maximizing CPU utilization by keeping multiple processes in memory.
- **Protection:** Ensuring that processes do not interfere with each other's memory spaces or the operating system's memory.
- **Relocation:** Allowing programs to be loaded into any available memory location.
- **Sharing:** Enabling multiple processes to share common code or data.
- **Logical Organization:** Providing a logical view of memory that is independent of physical memory.

## **4.1.2. Monoprogramming vs. Multiprogramming**

### **Monoprogramming:**

- **Explanation:** In a monoprogramming system, only one program resides in main memory at a time and has exclusive control over the CPU and memory. Once that program starts, it runs to completion before another program can be loaded.
- **Advantages:**
  - Simple memory management.
  - No need for complex protection mechanisms between user programs.
- **Disadvantages:**
  - Extremely low CPU utilization, especially when the single program performs I/O operations (the CPU remains idle).
  - No concurrency; inefficient use of computing resources.
- **Example:** Early MS-DOS systems before multitasking features were widely adopted.

### **Multiprogramming:**

- **Explanation:** Multiprogramming is a technique where the operating system keeps multiple user programs in main memory simultaneously. When one program is performing a slow operation (like I/O), the CPU switches to another program that is ready to execute. This significantly increases CPU utilization and overall system throughput.
- **Advantages:**
  - Higher CPU utilization.
  - Increased system throughput (more jobs completed per unit time).
  - Better interactive response time for multiple users (in time-sharing systems).
- **Disadvantages:**
  - Requires more complex memory management to allocate and protect memory for multiple programs.
  - Requires CPU scheduling to manage context switching between programs.
  - Increased overhead for the OS.

- **Example:** Modern operating systems like Linux, Windows, macOS, which allow users to run multiple applications concurrently (e.g., web browser, word processor, music player all open at once).

### 4.1.3. Modelling Multiprogramming

Multiprogramming efficiency can be modeled to understand its benefits. A simple probabilistic model can be used to estimate CPU utilization.

- **Assumptions:** A system with  $N$  processes in memory, and each process spends a fraction  $p$  of its time waiting for I/O.
- **CPU Utilization Formula:** The probability that all  $N$  processes are waiting for I/O is  $p^N$ . Therefore, the CPU utilization is  $1 - p^N$ .
- **Practical Example:** If a process spends 80% ( $p=0.8$ ) of its time on I/O, then:
  - With monoprogramming ( $N=1$ ): CPU utilization =  $1 - 0.8^1 = 0.2$  (20%).
  - With 4 processes ( $N=4$ ): CPU utilization =  $1 - 0.8^4 = 1 - 0.4096 = 0.5904$  (approx. 59%).
  - This model demonstrates how CPU utilization significantly increases with a higher degree of multiprogramming, especially when processes are I/O-bound.

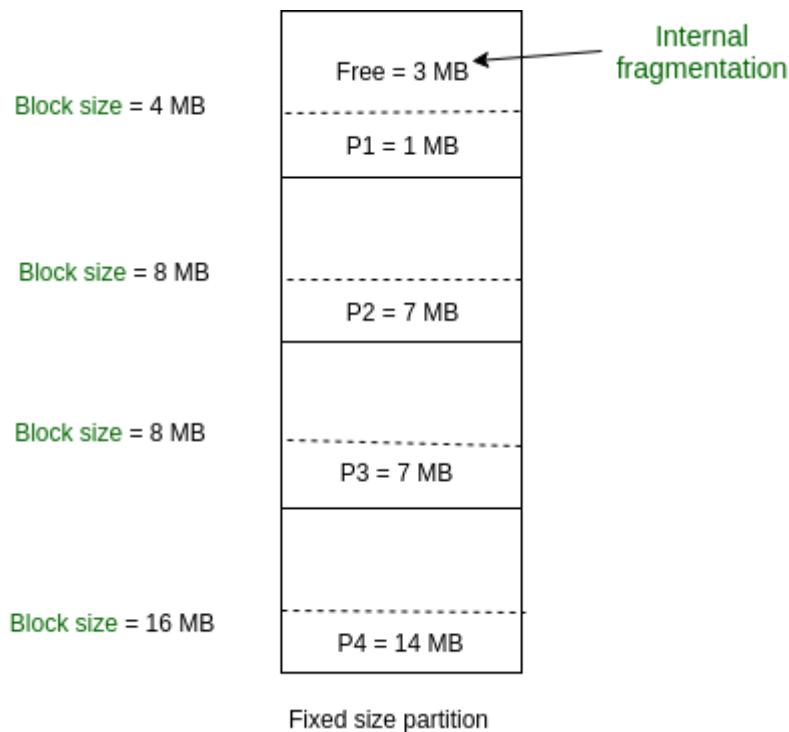
### 4.1.4. Multiprogramming with Fixed and Variable Partitions

These are early memory management techniques for multiprogramming:

#### Fixed Partitions (Static Partitioning):

- **Explanation:** Main memory is divided into a fixed number of partitions at system startup. Each partition has a predefined size. A program can be loaded into any partition that is large enough to hold it.
- **Types:**
  - **Equal-sized partitions:** All partitions have the same size.
  - **Unequal-sized partitions:** Partitions have different sizes to accommodate programs of various memory requirements.
- **Advantages:**
  - Simple to implement.
  - Relatively low overhead.
- **Disadvantages:**
  - **Internal Fragmentation:** If a program is loaded into a partition larger than its actual size, the unused space within that partition is wasted.
  - **Limited Degree of Multiprogramming:** The number of active programs is limited by the number of fixed partitions.
  - **Fixed Partition Size:** Cannot load a program larger than the largest partition.
- **Example:** A 1MB memory divided into four 256KB partitions. If a 100KB program loads into a 256KB partition, 156KB is wasted (internal fragmentation).

**Diagram: Fixed Partitions**

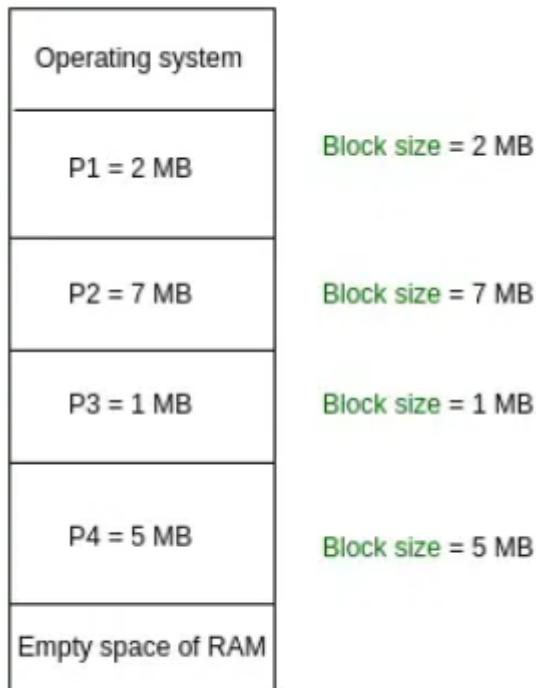


#### Variable Partitions (Dynamic Partitioning):

- **Explanation:** Memory is not partitioned beforehand. When a program needs to be loaded, the OS allocates a contiguous block of memory exactly equal to the program's size. When a program terminates, its memory is returned to a pool of free memory, potentially creating small, non-contiguous free blocks (holes).
- **Advantages:**
  - **No Internal Fragmentation:** Memory is allocated exactly to the program's needs.
  - More efficient use of memory compared to fixed partitions.
  - Degree of multiprogramming is limited only by total memory, not number of fixed partitions.
- **Disadvantages:**
  - **External Fragmentation:** As processes are loaded and unloaded, memory becomes fragmented into many small, non-contiguous free blocks. These small holes might collectively be large enough to satisfy a new request, but no single hole is large enough. This makes it difficult to allocate larger programs.
  - More complex to implement.
  - Requires **compaction** to alleviate external fragmentation, which is a costly operation that moves all processes to one end of memory to consolidate free space.
- **Example:** A 5MB memory. Process A (2MB) loads. Process B (1MB) loads. Process A terminates, leaving a 2MB hole. Process C (3MB) wants to load, but the 2MB hole is too small. Even though 4MB total free space might exist, it's fragmented.

**Diagram: Variable Partitions and External Fragmentation**

## Dynamic partitioning



Partition size = process size

So, no internal Fragmentation

Comparison Table: Fixed vs. Variable Partitions

Feature	Fixed Partitions	Variable Partitions
Memory Allocation	Pre-divided, static size	Dynamic, exact size of process
Internal Fragmentation	Yes, significant	No
External Fragmentation	No (or minimal)	Yes, significant
Degree of Multiprogramming	Limited by number of partitions	Limited by total memory size
Complexity	Simple	More complex
Compaction Required	No	Yes, to reduce external fragmentation

### 4.1.5. Relocation and Protection

#### Relocation:

- Explanation: Relocation refers to the ability to load a process into any available contiguous block of physical memory, rather than requiring it to load

at a fixed, predefined address. This is crucial for multiprogramming, as memory becomes fragmented and processes need to be moved or loaded where space is available.

- **Types of Addresses:**

- **Logical Address (Virtual Address):** The address generated by the CPU. This address is relative to the start of the program and does not change regardless of where the program is loaded in physical memory.
- **Physical Address (Absolute Address):** The actual address in main memory.

- **Mechanism:**

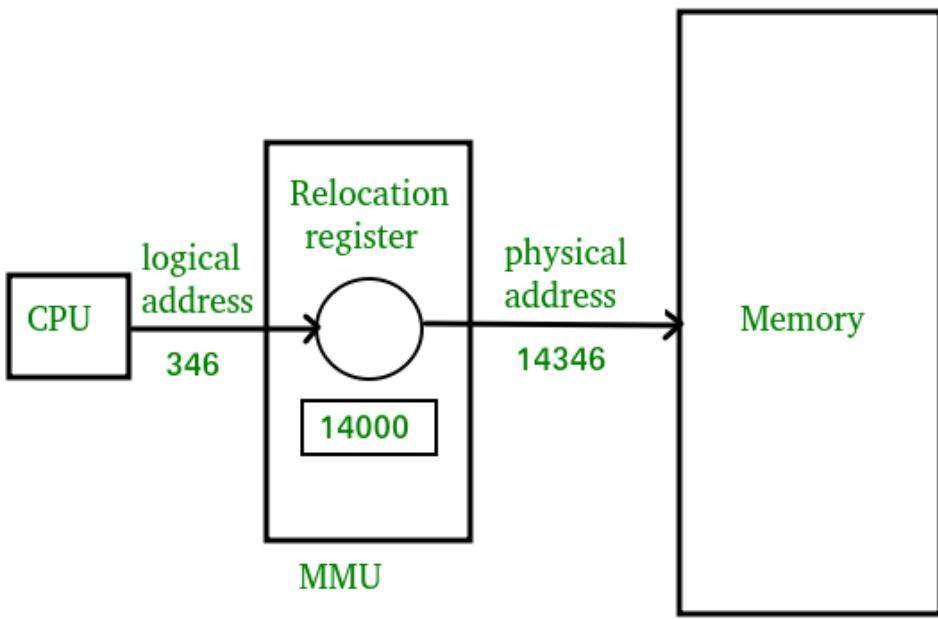
- **Static Relocation:** Done at load time. The loader modifies all logical addresses in the program to physical addresses before execution. This means a program, once loaded, cannot be moved.
- **Dynamic Relocation (Runtime Relocation):** Done at runtime by the MMU. The CPU generates logical addresses, and a hardware mechanism (often using a **Relocation Register / Base Register** and a **Limit Register**) adds the base address of the process to the logical address to get the physical address. This allows the program to be moved in memory after loading.
  - **Base Register:** Contains the starting physical address of the process in memory.
  - **Limit Register:** Contains the size of the process's memory region, ensuring that addresses generated do not exceed the allocated space.

- **Advantages of Dynamic Relocation:**

- Allows processes to be loaded into any available memory block.
- Facilitates swapping and compaction.
- Enables memory protection.

- **Example:** If a program's logical address is 100 and it's loaded into physical memory starting at address 5000 (stored in the Base Register), the MMU translates 100 to  $5000 + 100 = 5100$ .

**Diagram: Dynamic Relocation**



#### Protection:

- Explanation:** In a multiprogramming environment, it's crucial to protect the memory space of one process from being accessed or corrupted by another process, and also to protect the OS kernel's memory from user processes.
- Mechanism (with Dynamic Relocation):** The **Limit Register** plays a key role in memory protection. For every memory access, the MMU checks if the logical address generated by the CPU is within the bounds of the process's allocated memory segment (i.e., less than the value in the Limit Register). If the address is out of bounds, a hardware trap (memory protection error) is generated, preventing the access.
- Practical Example:** If Process A has a base address of 1000 and a limit of 500 (meaning it occupies physical addresses 1000-1499), and it tries to access logical address 600, the MMU would calculate  $1000 + 600 = 1600$ . Since 1600 is greater than its limit of 1499, a protection fault would occur, and the OS would terminate Process A.

#### 4.2.1. Memory Management with Bitmaps

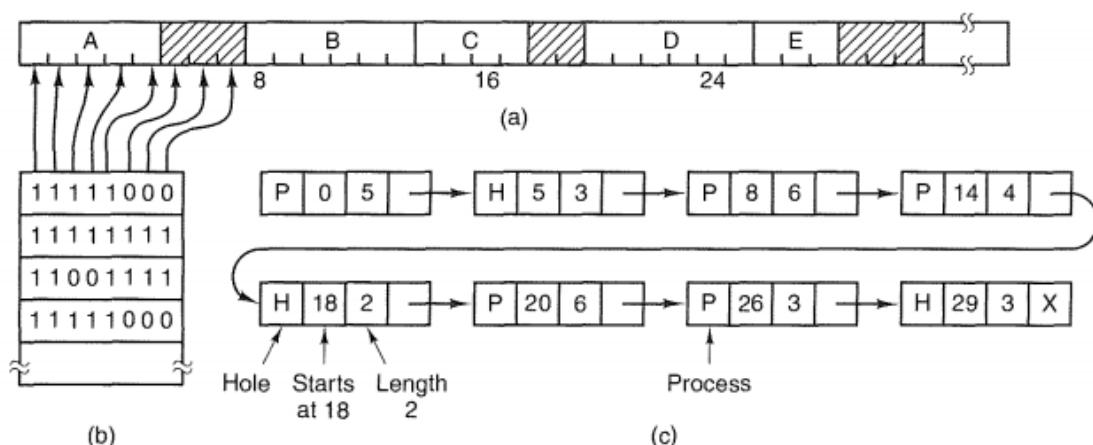
- Explanation:** Memory is divided into fixed-size allocation units (e.g., 4 KB, 8 KB). A bitmap is a bit array where each bit corresponds to one allocation unit. A bit value of '0' indicates the unit is free, and '1' indicates it's occupied (or vice-versa).
- Advantages:**
  - Simplicity of implementation.
  - Easy to find a block of N free units by searching for N consecutive '0' bits.
- Disadvantages:**

- Searching for a contiguous block of memory can be slow, as it involves scanning the bitmap.
- The size of the bitmap depends on the size of the allocation unit. A smaller unit size leads to a larger bitmap but potentially less internal fragmentation.
- Not ideal for variable-sized memory blocks.
- **Example:** If memory is 1MB and allocation unit is 4KB, there are 256 allocation units. The bitmap would be 256 bits (32 bytes).

#### 4.2.2. Memory Management with Linked-Lists

- **Explanation:** A linked list is maintained for all free and occupied memory blocks. Each node in the list represents a block of memory and contains information such as:
  - Starting address of the block.
  - Size of the block.
  - Status (free or occupied).
  - Pointers to the next and previous blocks in the list.
- **Advantages:**
  - Flexible for handling variable-sized blocks.
  - Easy to coalesce (merge) adjacent free blocks when a process is deallocated.
- **Disadvantages:**
  - Searching for a suitable free block can still be slow as it requires traversing the list.
  - Maintaining the list (insertion, deletion, merging) adds overhead.
- **Example:** A list could look like: (Occupied, Address 0, Size 200KB) -> (Free, Address 200KB, Size 100KB) -> (Occupied, Address 300KB, Size 500KB) -> (Free, Address 800KB, Size 200KB).

**Diagram: Memory Linked List**



**Figure 3-6.** (a) A part of memory with five processes and three holes. The tick marks show the memory allocation units. The shaded regions (0 in the bitmap) are free. (b) The corresponding bitmap. (c) The same information as a list.

### 4.2.3. Memory Allocation Strategies (for Variable Partitions)

When a process requests memory, and the OS uses a linked list of free blocks, it needs a strategy to choose which free block to allocate.

#### 1. First-Fit:

- **Explanation:** The OS scans the list of free blocks from the beginning and allocates the *first* free block that is large enough to satisfy the request.
  - **Advantages:** Simple and generally fast as it doesn't require extensive searching.
  - **Disadvantages:** Tends to leave small, unusable fragments at the beginning of memory, leading to more external fragmentation over time.
- **Example:** Free blocks: 10KB, 20KB, 5KB, 30KB. Request: 12KB. First-Fit allocates the 20KB block, leaving 8KB.

#### 2. Best-Fit:

- **Explanation:** The OS searches the entire list of free blocks and allocates the *smallest* free block that is large enough to satisfy the request.
  - **Advantages:** Tends to leave larger contiguous free blocks available, which might be useful for future large requests.
  - **Disadvantages:** Requires searching the entire list, which is slower. It tends to leave many very small, unusable holes (external fragmentation) that are too small for future requests.
- **Example:** Free blocks: 10KB, 20KB, 5KB, 30KB. Request: 12KB. Best-Fit allocates the 20KB block, leaving 8KB. (If there was a 15KB block, it would pick that, leaving 3KB).

#### 3. Worst-Fit:

- **Explanation:** The OS searches the entire list of free blocks and allocates the *largest* free block that is large enough to satisfy the request.
  - **Advantages:** Aims to leave a large remaining free block, hoping it's big enough for subsequent requests. Some argue it creates fewer very small unusable fragments.
  - **Disadvantages:** Requires searching the entire list (slow). By always using the largest block, it quickly breaks down large free blocks, which might be needed for larger processes later.
- **Example:** Free blocks: 10KB, 20KB, 5KB, 30KB. Request: 12KB. Worst-Fit allocates the 30KB block, leaving 18KB.

**Comparison Table: Memory Allocation Strategies**

Strategy	Explanation	Advantages	Disadvantages
First-Fit	Allocates the first sufficiently large block	Simple, fast	Tends to fragment the beginning of memory, higher external fragmentation.

<b>Best-Fit</b>	Allocates the smallest sufficiently large block	Leaves largest holes intact	Slow (full scan), creates many tiny unusable fragments (more external fragmentation).
<b>Worst-Fit</b>	Allocates the largest sufficiently large block	Tries to leave a large usable remnant	Slow (full scan), breaks down large free blocks quickly.

Consider a swapping system in which memory consists of the following hole sizes in memory order: 15 MB, 2 MB, 10 MB, 6 MB, 8 MB and 20 MB.

Which hole is taken for successive segment requests of:

- (a) 10 MB
- (b) 10 MB

For first fit, next fit and best fit.

We are given:

- **Initial holes(free memory) in memory (in order):** 15 MB, 2 MB, 10 MB, 6 MB, 8 MB, 20 MB
- **Requests:** (a) 10 MB (b) 10 MB

#### a. First Fit:

**Strategy:** Allocate the first hole that is big enough.

#### Step-by-step:

1. First 10 MB request:
  - 15 MB is big enough → **allocate 10 MB from 15 MB**
  - New holes: 5 MB, 2 MB, 10 MB, 6 MB, 8 MB, 20 MB
2. Second 10 MB request:
  - 5 MB → too small
  - 2 MB → too small
  - 10 MB → fits → **allocate 10 MB**
  - Final holes: 5 MB, 2 MB, 6 MB, 8 MB, 20 MB

**Answer (First Fit):** (a) 15 MB hole (b) 10 MB hole

#### b. Next Fit:

**Strategy:** Same as first fit, but continue searching from where the last allocation occurred (circular if needed).

#### Step-by-step:

1. First 10 MB request:
  - Start from beginning → 15 MB → allocate
  - Pointer now at next hole (2 MB)
  - Holes: 5 MB, 2 MB, 10 MB, 6 MB, 8 MB, 20 MB

2. Second 10 MB request:

- Start at 2 MB → too small
- 10 MB → fits → allocate
- Pointer now at 6 MB
- Holes: 5 MB, 2 MB, 6 MB, 8 MB, 20 MB

**Answer (Next Fit):** (a) 15 MB hole (b) 10 MB hole

c. **Best Fit:**

**Strategy:** Choose the **smallest hole** that is big enough (to reduce waste).

**Step-by-step:**

1. First 10 MB request:

- Candidates: 15 MB, 10 MB, 20 MB
- **Best fit = 10 MB** → allocate
- Holes: 15 MB, 2 MB, 6 MB, 8 MB, 20 MB

2. Second 10 MB request:

- Candidates: 15 MB, 20 MB
- **Best fit = 15 MB** → allocate
- Final holes: 5 MB, 2 MB, 8 MB, 20 MB

**Answer (Best Fit):** (a) 10 MB hole (b) 15 MB hole

**Final Summary:**

Strategy	(a) Hole Used	(b) Hole Used
First Fit	15 MB	10 MB
Next Fit	15 MB	10 MB
Best Fit	10 MB	15 MB

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#### 4.3.1. Virtual Memory

- **Explanation:** Virtual memory is a memory management technique that allows a program to execute even if only a portion of its address space is loaded into physical memory. It creates the illusion that processes have access to a very large, contiguous address space, even if the physical memory is fragmented or smaller than the virtual address space.

- **Purpose:**

- Allows programs to be larger than physical memory.
- Allows more programs to run concurrently than would fit in physical memory (increased degree of multiprogramming).
- Simplifies program loading (programs can be written as if they have unlimited memory).
- Facilitates memory protection and sharing.

- **Key Idea:** Separates the user's logical view of memory from the physical view of memory.

#### 4.3.2. Paging

- **Explanation:** Paging is a virtual memory technique that divides a process's logical address space into fixed-size blocks called **pages**. The physical memory (RAM) is similarly divided into fixed-size blocks called **frames** (or page frames), with the same size as pages. When a program executes, its pages are loaded into any available physical frames. The OS maintains a **page table** for each process to map its virtual pages to physical frames.
- **Advantages:**
  - **Eliminates External Fragmentation:** Since physical memory is allocated in fixed-size frames, there's no problem of finding a contiguous block of variable size. Any free frame can hold any page.
  - **Simple Memory Allocation:** Just find a free frame.
  - Enables efficient swapping to secondary storage (disk) at page granularity.
  - Facilitates shared memory by allowing multiple processes to share the same physical frames.
- **Disadvantages:**
  - **Internal Fragmentation:** A process's last page may not be entirely filled, leading to wasted space within that page (average half a page per process).
  - **Overhead of Page Tables:** Page tables themselves consume memory.
  - Increased complexity of address translation (requires MMU).

#### 4.3.3. Page Table and Page Table Structure

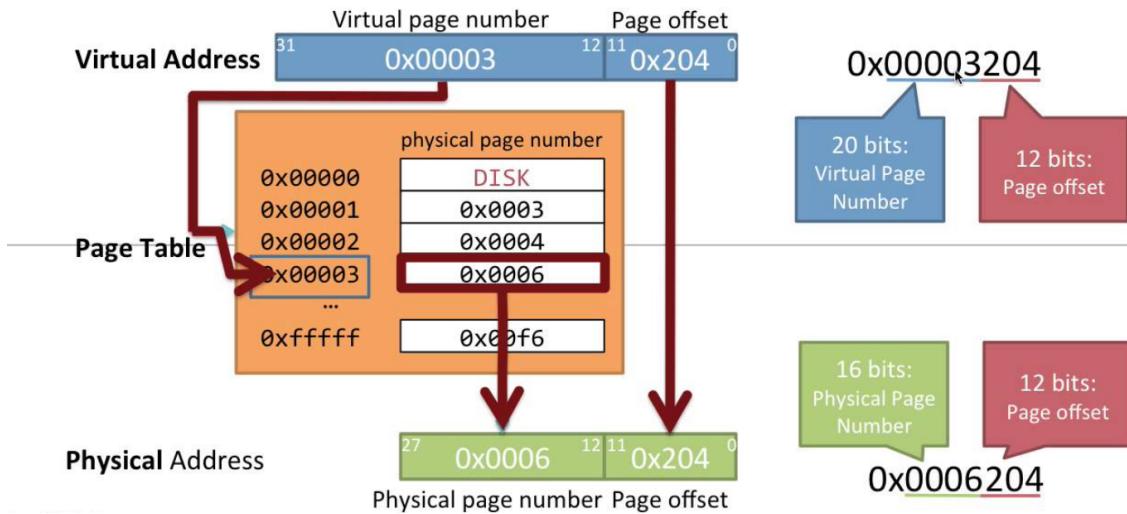
##### a. Page Table Definition & Purpose:

- A page table is a data structure, typically stored in main memory, that maps a process's logical page numbers to physical frame numbers. Each process has its own page table.
- It is used by the MMU (Memory Management Unit) to translate logical addresses (Page Number, Offset) into physical addresses (Frame Number, Offset).

##### b. Page Table Entry (PTE) Structure: Each entry in a page table typically contains:

- **Frame Number:** The physical address of the page frame in main memory.
- **Valid/Invalid Bit:** Indicates if the page is currently in physical memory.
- **Protection Bits:** (Read/Write/Execute) define access permissions.
- **Dirty Bit (Modified Bit):** Set if the page has been modified.
- **Accessed Bit (Reference Bit):** Set if the page has been read or written.
- Other bits (Cache Disable, Global, etc.).

**Diagram: Address Translation**



c. **Page Table Structures:** To manage the size and lookup efficiency of page tables, especially for large address spaces:

#### 1. Linear (Flat) Page Table:

- **Explanation:** A simple, single-level array where the page number directly indexes the PTE.
- **Disadvantages:** Inefficient for large, sparse address spaces as it requires an entry for every possible virtual page, consuming large amounts of memory for the table itself.

#### 2. Hierarchical Paging (Multi-Level Page Tables):

- **Explanation:** Breaks the page table into multiple levels (e.g., two-level, three-level). The logical address is divided into multiple page number components, each used as an index into a successive level of page tables. Only the portions of the page table corresponding to active memory regions need to be in RAM.
- **Advantages:** More memory efficient for sparse address spaces.
- **Disadvantages:** Slower lookup time due to multiple memory accesses for translation (mitigated by TLB).
- **Example:** A 64-bit system might use 4 or 5 levels of page tables.
- **Diagram:** Two-Level Paging (Review from previous section)\*
- (Mention to insert the same "Two-Level Paging Address Translation" diagram from the previous response here.)\*

#### 3. Hashed Page Tables:

- **Explanation:** Uses a hash function to map virtual page numbers to entries in a hash table, where each entry typically points to a linked list. Suitable for very large, sparse address spaces.
- **Disadvantages:** Variable lookup time depending on hash collisions.

#### 4. Inverted Page Tables:

- **Explanation:** Has only one page table for the entire system, with an entry for each *physical frame*. Each entry stores the virtual page number and process ID of the page currently residing in that frame.
- **Advantages:** Reduces the memory required for page tables (size is proportional to physical memory, not virtual address space).

- **Disadvantages:** Very slow lookup (requires searching the table) unless combined with a TLB or associative memory.

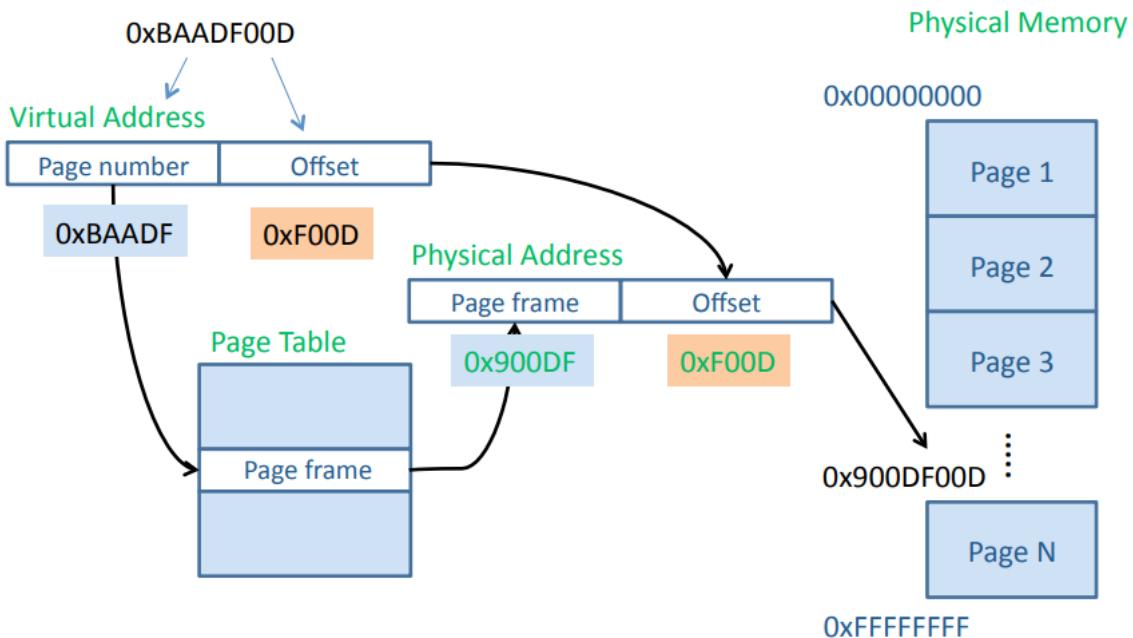
#### 4.3.4. Handling Page Faults

A **page fault** is a type of interrupt (trap) that occurs when a program tries to access a page that is part of its logical address space but is not currently loaded into a physical frame in main memory (i.e., its Valid/Invalid bit in the PTE is '0').

**Steps for Handling a Page Fault:**

1. **Trap to OS:** The MMU detects that the valid/invalid bit for the requested page is '0' and generates a page-fault trap, transferring control to the OS kernel.
2. **Save Process State:** The OS saves the state of the CPU registers and the process's context so it can resume execution later.
3. **Validate Address:** The OS determines if the logical address is valid (i.e., within the process's allocated virtual address space) and if the attempted memory access is permitted by protection bits. If not, the process is terminated (e.g., segmentation fault).
4. **Locate Page on Disk:** If the address is valid, the OS looks up the page in its internal tables (e.g., swap space table) to find its location on secondary storage (swap disk).
5. **Find Free Frame:** The OS finds a free physical frame in main memory.
  - If a free frame is available, it's used.
  - If no free frame is available, a **page replacement algorithm** is invoked to select a victim page to evict from memory.
6. **Swap Out (if necessary):** If a victim page was selected and it was 'dirty' (modified), its contents must be written back to the swap disk to ensure data integrity.
7. **Read Page In:** The OS schedules a disk I/O operation to read the required page from the swap disk into the newly freed (or chosen) physical frame. This is a slow operation.
8. **Update Page Table:** Once the page is loaded, the OS updates the page table entry for that page:
  - Sets the Frame Number to the new physical frame.
  - Sets the Valid/Invalid bit to '1' (valid).
  - Resets the Accessed bit to '0' and Dirty bit to '0'.
9. **Restart Instruction:** The CPU registers and process context are restored, and the instruction that caused the page fault is restarted. Since the page is now in memory, the instruction will complete successfully.

**Diagram: Page Fault Handling**



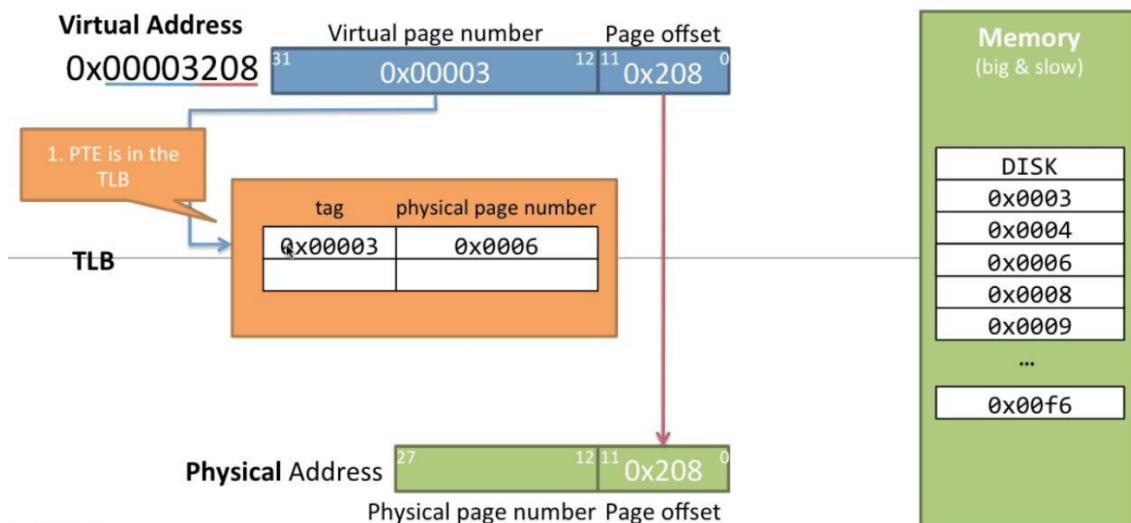
#### 4.3.5. TLBs (Translation Lookaside Buffers)

- **Explanation:** As mentioned earlier, page tables reside in main memory. Accessing the page table for every memory reference would effectively double the memory access time, leading to significant performance degradation. The **Translation Lookaside Buffer (TLB)** is a small, fast, associative cache built into the MMU hardware that stores recently used page number to frame number translations.
- **Mechanism:**
  1. When the CPU generates a logical address, the MMU first checks the TLB in parallel.
  2. **TLB Hit:** If the page number is found in the TLB, the corresponding frame number is retrieved almost instantly (typically within one CPU cycle). The physical address is formed, and the memory access proceeds without touching main memory for the translation.
  3. **TLB Miss:** If the page number is not found in the TLB, the MMU must then perform the full page table lookup in main memory (which might involve multiple memory accesses for hierarchical page tables).
  4. Once the translation (Frame Number) is found from the page table, it is loaded into the TLB (potentially replacing an older entry using a replacement policy like LRU), and then the physical address is formed.
- **Advantages:**
  - **Significantly Speeds Up Address Translation:** Reduces the average memory access time.
  - Exploits **locality of reference** (temporal and spatial locality): If a page is accessed, it's likely to be accessed again soon (temporal) or nearby pages will be accessed (spatial), leading to high TLB hit rates.
- **Disadvantages:**
  - **Cost:** TLBs are hardware, making them expensive and thus limited in size.
  - **Context Switch Overhead:** When a context switch occurs, the TLB needs to be flushed entirely (if entries are not tagged with process IDs) to prevent the new process from using stale translations of the previous

process. This causes a temporary performance dip as the TLB needs to be refilled.

- **Hit Rate:** The percentage of times the requested page number is found in the TLB. A typical hit rate is 90% or higher.

**Diagram: TLB in Address Translation (Review from previous section)**



#### Page Table vs TLB

Feature	Page Table	TLB (Translation Lookaside Buffer)
Type	Data Structure	Hardware Cache (Associative Memory)
Location	Main Memory (RAM)	CPU (within the Memory Management Unit - MMU)
Purpose	Authoritative virtual-to-physical mapping	Speed up virtual-to-physical address translation
Size/Capacity	Can be very large (depends on virtual address space and hierarchy)	Very small (tens to thousands of entries)
Access Speed	Slower (requires memory access/es)	Much faster (on-chip, near CPU speed)
Management	Primarily managed by OS (software)	Primarily managed by MMU hardware (with OS flushing)
Behavior on Miss	Triggers OS to load missing page (page fault) if not in memory	Triggers a lookup in the Page Table (hardware/OS)

#### 4.4.1. Concept of Locality of Reference

- **Explanation:** This is a fundamental principle that underlies the effectiveness of caching (including TLBs) and virtual memory. It states that during any interval of time, programs tend to access a relatively small portion of their address space.
  - **Temporal Locality:** If a memory location is accessed, it is likely to be accessed again very soon. (e.g., loop variables, frequently called functions).
  - **Spatial Locality:** If a memory location is accessed, memory locations nearby it are likely to be accessed soon. (e.g., arrays, sequential code execution).
- **Implication for Paging:** If a program exhibits strong locality, only a small "working set" of its pages needs to be in memory at any given time to avoid frequent page faults. Page replacement algorithms leverage this.

#### 4.4.2. Page Replacement Algorithms

##### 1. FIFO (First-In, First-Out)

- **Explanation:** The page that has been in memory for the longest time is replaced. It treats pages as a queue; the page at the head of the queue (oldest) is removed.
- **Total Page Faults:** Counted at the end.

Assume a given number of available frames and a reference string (sequence of page accesses).

- Reference String: 7, 0, 1, 2, 0, 3, 0, 4, 2, 3, 0, 3, 2, 3
- Frame size: 3

Schedule table

Ref	7,	0,	1,	2,	0,	3,	0,	4,	2,	3,	0,	3,	2,	3
fr	7,	7,	7,	2,	2,	2,	4,	4,	4,	4,	0,	0,	0,	0,
fr		0,	0,	0,	0,	3,	3,	3,	2,	2,	2,	2,	2,	3
fr			1,	1,	1,	1,	0,	0,	0,	3,	3,	3,	3,	3,
Hit	x	x	x	x	✓	x	x	x	x	x	✓	✓	✓	x

#### Summary

Number of references: 14

Number of pages: 7

Algorithm used: FIFO

Number of frames: 3

Hit rate: 0.21

Miss rate: 0.79

C/W:

## Schedule table

Ref	3	2	1	3	4	1	6	2	4	3	4	2	1	4	5	2	1	3	4
fr	3	3	3	3	4	4	4	4	4	3	3	3	3	3	5	5	5	5	4
fr		2	2	2	2	2	6	6	6	6	4	4	4	4	4	2	2	2	2
fr			1	1	1	1	1	2	2	2	2	2	1	1	1	1	1	3	3
Hit	x	x	x	x	✓	x	✓	x	x	✓	x	x	✓	x	✓	x	✓	x	x

## Summary

Number of references: 19

Number of pages: 6

Algorithm used: FIFO

Number of frames: 3

Hit rate: 0.32

Miss rate: 0.68

## 2. LRU (Least Recently Used)

- **Explanation:** The page that has not been used for the longest period of time is replaced.
- **Total Page Faults:** Counted at the end.

Assume a given number of available frames and a reference string (sequence of page accesses).

- Reference String: 7, 0, 1, 2, 0, 3, 0, 4, 2, 3, 0, 3, 2, 3
- Frame size: 3

## Schedule table

Ref	7,	0,	1,	2,	0,	3,	0,	4,	2,	3,	0,	3,	2,	3
fr	7,	7,	7,	2,	2,	2,	2,	4,	4,	4,	0,	0,	0,	3
fr		0,	0,	0,	0,	0,	0,	0,	0,	3,	3,	3,	3,	3,
fr			1,	1,	1,	3,	3,	3,	2,	2,	2,	2,	2,	2,
Hit	x	x	x	x	✓	x	✓	x	x	x	x	✓	✓	x

## Summary

Number of references: 14

Number of pages: 7

Algorithm used: LRU

Number of frames: 3

**Hit rate:** 0.29

**Miss rate:** 0.71

C/W:

## Schedule table

Ref	3	2	1	3	4	1	6	2	4	3	4	2	1	4	5	2	1	3	4
fr	3	3	3	3	3	3	6	6	6	3	3	3	1	1	1	2	2	2	4
fr		2	2	2	4	4	4	2	2	2	2	2	2	2	5	5	5	3	3
fr			1	1	1	1	1	1	4	4	4	4	4	4	4	4	1	1	1
Hit	x	x	x	✓	x	✓	x	x	x	x	x	✓	✓	x	x	x	x	x	x

## Summary

Number of references: 19

Number of pages: 6

Algorithm used: LRU

Number of frames: 3

**Hit rate:** 0.26

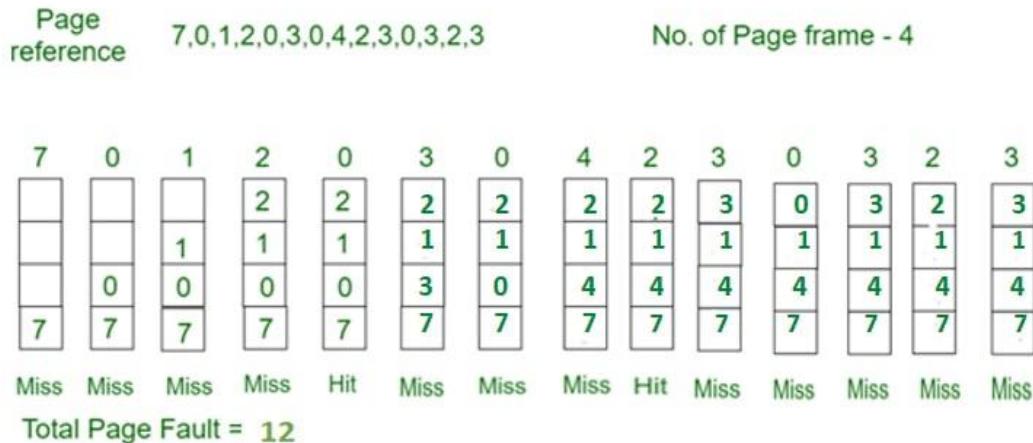
**Miss rate:** 0.74

## 3. Most Recently Used (MRU)

- Explanation:** In this algorithm, page will be replaced which has been used recently.
- Total Page Faults:** Counted at the end.

Assume a given number of available frames and a reference string (sequence of page accesses).

- Reference String: 7, 0, 1, 2, 0, 3, 0, 4, 2, 3, 0, 3, 2, 3
- Frame size: 3



#### 4. Optimal (MIN)

- **Explanation:** The page that will *not* be used for the longest period of time in the future is replaced. In this algorithm, we are looking into the future or "predicting." If a page fault occurs, we simply look at the sequence of page references to see which page in the frame will not be used for the longest time. Despite the fact that this algorithm has the lowest page-fault rate of all algorithms, it is not practical since it is hard to predict the future.
- **Total Page Faults:** Counted at the end.

Assume a given number of available frames and a reference string (sequence of page accesses).

- Reference String: 7, 0, 1, 2, 0, 3, 0, 4, 2, 3, 0, 3, 2, 3
- Frame size: 3

## Schedule table

Ref	7,	0,	1,	2,	0,	3,	0,	4,	2,	3,	0,	3,	2,	3
fr	7,	7,	7,	2,	2,	2,	2,	2,	2,	2,	2,	2,	2,	3
fr		0,	0,	0,	0,	0,	0,	4,	4,	4,	0,	0,	0,	0,
fr			1,	1,	1,	3,	3,	3,	3,	3,	3,	3,	3,	3,
Hit	x	x	x	x	✓	x	✓	x	✓	✓	x	✓	✓	x

## Summary

Number of references: 14

Number of pages: 7

Algorithm used: OPTIMAL

Number of frames: 3

Hit rate: 0.43

Miss rate: 0.57

## C/W:

## Schedule table

Ref	3	2	1	3	4	1	6	2	4	3	4	2	1	4	5	2	1	3	4
fr	3	3	3	3	4	4	4	4	4	4	4	4	4	4	5	5	5	3	4
fr		2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2
fr			1	1	1	1	6	6	6	3	3	3	1	1	1	1	1	1	1
Hit	x	x	x	✓	x	✓	x	✓	✓	x	✓	✓	x	✓	x	✓	✓	x	x

## Summary

Number of references: 19

Number of pages: 6

Algorithm used: OPTIMAL

Number of frames: 3

Hit rate: 0.47

Miss rate: 0.53

## 4. LFU (Least Frequently Used):

- **Explanation:** The page with the smallest count of accesses is replaced. A counter is associated with each page, and it's incremented on each access.
- **Advantages:** Potentially better than FIFO for some access patterns.

- **Disadvantages:** Does not account for aging. A page that was heavily used in the past but is no longer needed might stay in memory indefinitely because its count is high. Complex to implement exact counts.

Assume a given number of available frames and a reference string (sequence of page accesses).

- Reference String: 4, 7, 6, 1, 7, 6, 1, 2, 7, 2
- Frame size: 3

Step	Reference	Frame Content	Page Fault	Action
1	4	4	☐ Yes	Load 4 (count: 1)
2	7	4, 7	☐ Yes	Load 7 (count: 1)
3	6	4, 7, 6	☐ Yes	Load 6 (count: 1)
4	1	7, 6, 1	☐ Yes	Evict 4 (count: 1, oldest), load 1 (count: 1)
5	7	7, 6, 1	☐ No	7 used → increment count (7: 2)
6	6	7, 6, 1	☐ No	6 used → increment count (6: 2)
7	1	7, 6, 1	☐ No	1 used → increment count (1: 2)
8	2	6, 1, 2	☐ Yes	Evict 7 (count: 2, FIFO tie breaker), load 2 (count: 1)
9	7	1, 2, 7	☐ Yes	Evict 6 (count: 2, FIFO), load 7 (count: 1)
10	2	2, 7, 1	☐ No	2 used → increment count (2: 2)

**Total Page Faults (LFU): 6**

##### 5. Approximation of LRU (e.g., Clock / Second Chance):

- Due to the overhead of implementing true LRU/LFU, approximations are often used, which leverage the "Accessed Bit" (Reference Bit) in the PTE.
- **Second Chance (Enhanced FIFO):**
  - **Explanation:** This is a FIFO queue but with an added "second chance." When a page is selected for replacement (it's at the head of the FIFO queue), its "Accessed Bit" is checked.
    - If the Accessed Bit is '0', the page is truly old and hasn't been used recently, so it's evicted.
    - If the Accessed Bit is '1', the page is given a "second chance." The Accessed Bit is cleared ('0'), and the page is moved to the tail of the FIFO queue, as if it had just been loaded. The algorithm then proceeds to check the next page in the queue.
  - **Advantages:** Much simpler to implement than true LRU, but performs significantly better than pure FIFO by considering recent usage.

- **Disadvantages:** Still prone to Belady's Anomaly in some cases.

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

Ref	2	3	2	1	5	2	4	5	3	2	5	2
f1	2	2	2(1)	2(1)	2	2(1)	2	2	3	3	3	3
f2		3	3	3	5	5	5	5(1)	5(1)	5	5(2)	5(1)
f3				1	1	1	4	4	4	2	2	2(1)

No. of references = 12  
 No. of pages = 5  
 Algorithm used = Second chance  
 No. of frames = 3  
 Hit = Page faults = 7,  
 Miss =

- **Clock Algorithm:**

- **Explanation:** A circular list of pages is maintained (conceptually like a clock face). A "clock hand" pointer moves around the circle. When a page needs to be replaced, the hand advances.
  - If the page the hand points to has its Accessed Bit '0', that page is evicted.
  - If the Accessed Bit is '1', it's cleared ('0'), and the hand advances to the next page. This continues until a page with an '0' Accessed Bit is found.
- **Advantages:** Simpler and more efficient than LRU while providing good performance. Widely used in practice.
- **Disadvantages:** Can suffer from Belady's anomaly in specific scenarios.

- **WClock (Working Set Clock):**

- **Explanation:** An extension of the Clock algorithm that incorporates the **Working Set Model**. Each page frame has an "Accessed Bit" and a "time-of-last-use" stamp. The clock hand scans frames. If a page's Accessed Bit is '1', it's cleared and its "time-of-last-use" updated. If it's '0', the algorithm checks its "time-of-last-use" against a threshold ( $\delta$ ). If the page hasn't been used for  $\delta$  time, it's considered old and is a candidate for eviction. If it's still "fresh" (used within  $\delta$  time) or the hand makes a full circle, it might need to iterate again.
- **Advantages:** Closely approximates the Working Set Model (keeping useful pages) while remaining practical.

- **Disadvantages:** More complex than basic Clock.

**Numerical:** Refer to hamrocsit

#### 4.4.3. Belady's Anomaly

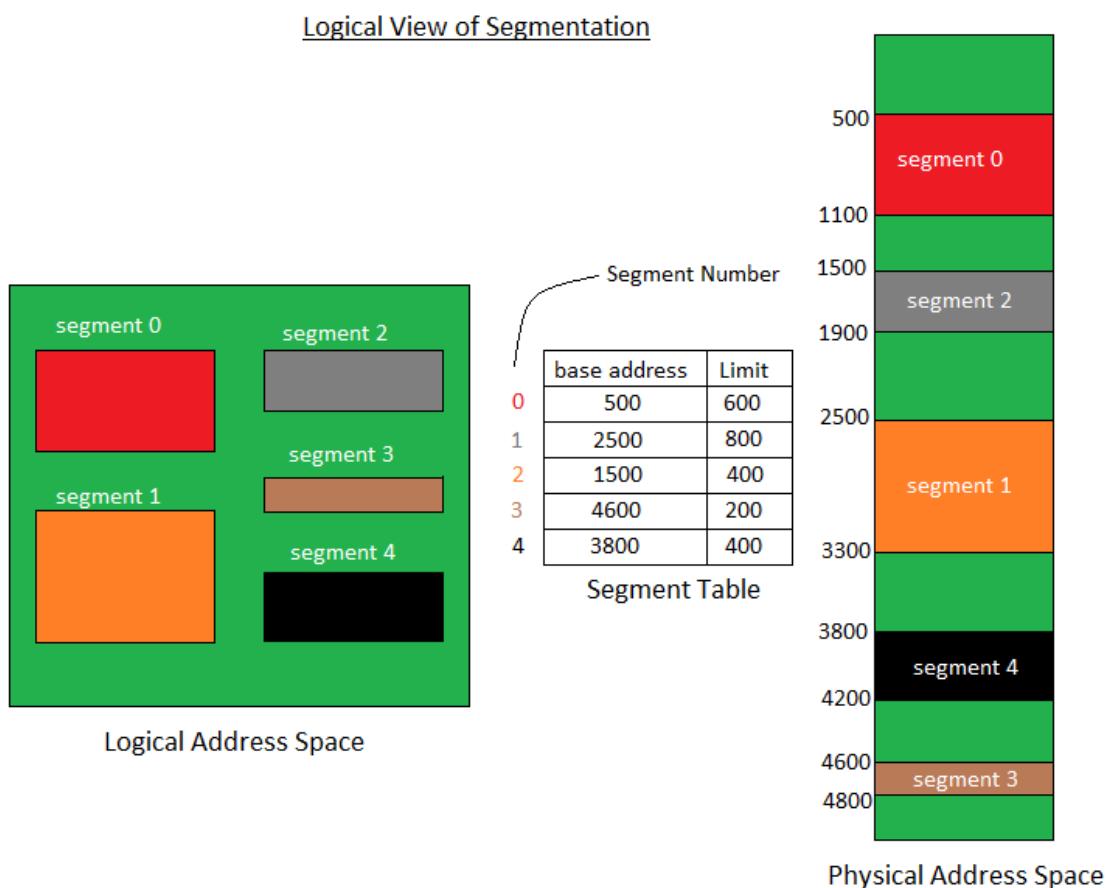
- **Explanation:** An undesirable phenomenon observed in some page replacement algorithms (like FIFO and Second Chance) where increasing the number of available physical frames can lead to an *increase* in the number of page faults for a given reference string.
- **Why it's an anomaly:** Intuitively, more memory should always lead to fewer faults. Belady's Anomaly demonstrates that this is not always true for all algorithms.
- **Algorithms Affected:** FIFO, Second Chance.
- **Algorithms Not Affected:** LRU, Optimal, LFU (Least Recently Used, Optimal, and Least Frequently Used are "stack algorithms" and provably do not suffer from Belady's Anomaly).
- **Practical Example (FIFO, with 3 vs. 4 frames):**
  - Reference String: 3, 2, 1, 0, 3, 2, 4, 3, 2, 1, 0, 4
  - **3 Frames:** 9 page faults
  - **4 Frames:** 10 page faults (An increase in faults despite more frames!)

#### 4.5.1. Segmentation

- **Explanation:** Segmentation is a memory management technique that views a program's logical address space as a collection of variable-sized segments. Each segment corresponds to a logical unit of the program, such as a code segment, data segment, stack segment, or subroutine. Programmers refer to addresses as (segment-number, offset-within-segment).
- **Need for Segmentation (Advantages):**
  - **User's View of Memory:** Maps directly to how programmers think about their programs (e.g., "my code segment," "my stack," "my data"). This makes programming easier and more intuitive.
  - **Protection:** Natural way to provide protection. Different access rights (read/write/execute) can be assigned to entire segments. A code segment can be made read-only, preventing accidental modification.
  - **Sharing:** Allows easy sharing of code or data segments between processes (e.g., shared libraries) without complex mechanisms.
  - **Dynamic Linking:** Facilitates dynamic linking of libraries, where segments can be loaded only when needed.
- **Mechanism:**
  1. The logical address is composed of a **segment number** and an **offset** within that segment.
  2. Each process has a **segment table**. A **Segment Table Base Register (STBR)** points to the beginning of the segment table in physical memory.
  3. Each entry in the segment table contains:
    - **Base Address:** The physical starting address of the segment in main memory.
    - **Limit:** The length (size) of the segment.
    - **Protection Bits:** Access rights for the segment.
  4. The MMU uses the **segment number** to index into the segment table.

5. It checks if the **offset** is less than the segment's **limit** (for protection).
6. If valid, the **base address** is added to the **offset** to get the physical address.

**Diagram: Segmentation Address Translation**



#### 4.5.2. Drawbacks of Segmentation:

- **External Fragmentation:** Since segments are variable-sized, segmentation is prone to external fragmentation, similar to variable partitioning. As segments are loaded and unloaded, memory can become fragmented into many small, unusable holes, even if the total free space is sufficient for a new segment.
- **Compaction:** To mitigate external fragmentation, memory compaction is necessary, which is a costly and time-consuming process involving moving segments in memory.
- **Complexity of Memory Management:** Managing variable-sized holes and performing compaction adds significant complexity to the OS.

**Problem**

Consider the segment table:

What are the physical address for the following logical addresses?

- a. 0,430
- b. 1,10
- c. 1,11
- d. 2,500

Segment	Base	Length
0	219	600
1	2300	14
2	90	100
3	1327	580
4	1952	965

To compute the **physical address** for a given **logical address (segment, offset)** using the segment table:

**Formula:**

$$\text{Physical Address} = \text{Base}[segment] + offset$$

But only if:

*offset < length[segment] Otherwise: it's an error (segmentation fault).*

**Segment Table**

Segment	Base	Length
0	219	600
1	2300	14
2	90	100
3	1327	580
4	1952	965

(a) 0,430

- Offset = 430 < 600 → valid
- Physical Address = 219 + 430 = **649**

(b) 1,10

- Offset = 10 < 14 → valid
- Physical Address = 2300 + 10 = **2310**

(c) 1,11

- Offset = 11 < 14 → valid
- Physical Address = 2300 + 11 = **2311**

(d) 2,500

- Offset = 500 > 100 → invalid
- Segmentation fault

**Final Answers:**

Logical Address	Physical Address / Error

(0, 430)	649
(1, 10)	2310
(1, 11)	2311
(2, 500)	Segmentation Fault (□)

#### 4.5.3. Segmentation with Paging (MULTICS)

- **Explanation:** To combine the benefits of both segmentation (user view, protection, sharing) and paging (no external fragmentation, efficient allocation), some systems use a hybrid approach: **Segmentation with Paging**. The famous MULTICS (Multiplexed Information and Computing Service) operating system was a pioneer in this approach.
- **Mechanism:**
  1. The logical address is still (segment-number, offset-within-segment).
  2. The **segment number** is used to access a **segment table** (similar to pure segmentation). Each entry in the segment table points to the *base address of a page table* for that specific segment.
  3. The **offset** within the segment is then treated as a **logical address for paging**. This offset is split into a (page-number, offset-within-page) pair.
  4. The **page number** (from the segment's offset) is used to index into the *segment's page table* (which was pointed to by the segment table entry).
  5. This page table entry provides the **physical frame number**.
  6. The **physical frame number** is combined with the **offset-within-page** to form the final physical address.
- **Advantages:**
  - **Combines Benefits:** Achieves the logical organization and protection of segmentation with the non-contiguous memory allocation and external fragmentation elimination of paging.
  - **Efficient Sharing:** Shared segments imply shared page tables.
  - **Reduced Internal Fragmentation:** Paging handles the fine-grained allocation.
- **Disadvantages:**
  - **Increased Complexity:** The most complex memory management scheme, requiring multiple levels of tables for translation.
  - **Increased Overhead:** Each memory access requires at least two memory lookups (one for the segment table, one for the page table) before the actual data access (mitigated by TLBs that store segment and page table entries).

#### Paging vs Segmentation

Feature	Paging	Segmentation
<b>Concept</b>	Divides program into fixed-size blocks (pages).	Divides program into logical, variable-size units (segments).
<b>User View</b>	Not visible to the user; memory appears as a single	Visible to the user; memory is viewed as a collection of

	linear address space.	segments, reflecting program structure.
<b>Address Space</b>	Single, 1-D (one-dimensional) virtual address space.	Multiple, 2-D (two-dimensional) virtual address spaces (segment number, offset).
<b>Internal Fragmentation</b>	Suffers from internal fragmentation (unused space within a page).	Does not suffer from internal fragmentation.
<b>External Fragmentation</b>	Does not suffer from external fragmentation.	Suffers from external fragmentation (unused space between segments).
<b>Complexity</b>	Relatively simple hardware implementation.	More complex hardware implementation (variable-size mapping).
<b>Security/Protection</b>	Protection is on a per-page basis.	Protection is on a per-segment basis, aligning with logical program units.
<b>Sharing</b>	Sharing of pages can be complex (e.g., shared code must align with page boundaries).	Easier to share segments (e.g., shared libraries, procedures).
<b>Main Table</b>	Page Table.	Segment Table.