MODULE 5

MEMORY MANAGEMENT

MEMORY HIERARCHY OVERVIEW

Computer memory is organized as a hierarchy based on **speed, cost, and capacity**. Faster memory is more expensive and smaller; slower memory is cheaper and larger.

General order (fastest → slowest): Registers → Cache → Main Memory (RAM) → Secondary Storage → Tertiary Storage

CPU REGISTERS

Description

- Small storage locations inside the CPU
- Hold operands, addresses, and intermediate results

Speed

- Fastest memory in the system
- Access time: ~1 CPU cycle (sub-nanosecond)

Cost

- Extremely high cost per bit
- Implemented using flip-flops

Capacity

- Very small (bytes to a few kilobytes per core)

Use Case

- Immediate data required for instruction execution

CACHE MEMORY

Description

- High-speed memory between CPU and RAM
- Stores frequently accessed data

Levels

- L1 Cache: Smallest, fastest
- L2 Cache: Larger, slightly slower
- L3 Cache: Shared, largest, slowest cache

Speed

- L1: ~1–2 ns
- L2: ~3–10 ns
- L3: ~10–20 ns

Cost

- Very high (SRAM-based)
- Cheaper than registers, costlier than RAM

Capacity

- KBs to tens of MBs

Use Case

- Reduce average memory access time

MAIN MEMORY (RAM)

Description

- Primary working memory for programs and data
- Volatile (data lost on power-off)

Type

- DRAM (Dynamic RAM)

Speed

- ~50–100 ns access time

Cost

- Moderate cost per bit
- Cheaper than cache, costlier than storage

Capacity

- Typically 4 GB to 128 GB+

Use Case

- Holds active programs and operating system

SECONDARY MEMORY (STORAGE)

Description

- Non-volatile long-term storage

Types

- SSD (Solid State Drive)
- HDD (Hard Disk Drive)

Speed

- SSD: ~50–100 μs
- HDD: ~5–10 ms

Cost

- Low cost per bit
- HDD cheaper than SSD

Capacity

- Hundreds of GBs to multiple TBs

Use Case

- Store OS, applications, and user data

TERTIARY / OFFLINE STORAGE

Description

- Used for backups and archival storage

Examples

- Magnetic tape
- Optical discs
- Cloud cold storage

Speed

- Very slow (seconds to minutes access time)

Cost

- Lowest cost per bit

Capacity

- Very large (TBs to PBs)

Use Case

- Long-term data retention and backups

Comparative Summary

Memory Type	**Speed**	**Cost per Bit**	**Capacity**
Registers	Fastest	Highest	Very Small
Cache	Very Fast	Very High	Small
RAM	Fast	Medium	Medium–Large
SSD / HDD	Slow	Low	Large
Tertiary	Slowest	Lowest	Very Large

Memory Management is a core function of an Operating System (OS) that handles the efficient use of primary memory (RAM).

It ensures that:

- Programs get the memory they need
- Memory is used efficiently
- Programs do not interfere with each other

DEFINITION OF MEMORY MANAGEMENT

Memory management refers to the process by which an operating system:

- Allocates memory to processes
- Deallocates memory when no longer needed
- Protects memory from unauthorized access
- Optimizes memory utilization and system performance

OBJECTIVES OF MEMORY MANAGEMENT

- Efficient utilization of memory
- Fast access to data and instructions
- Protection and isolation of processes
- Support for multitasking and multiprogramming
- Minimize fragmentation

MEMORY ALLOCATION

Memory Allocation is the process of assigning memory space to a program or process.

The OS:

- Keeps track of used and free memory blocks
- Allocates memory when a process starts

Types of Allocation

- Contiguous allocation
- Non-contiguous allocation

MEMORY DEALLOCATION

Memory Deallocation occurs when a process terminates or releases memory.

Importance:

- Prevents memory wastage
- Makes memory available for other processes
- Avoids memory leaks

The OS updates its memory management tables accordingly.

MEMORY PROTECTION

Memory Protection ensures that one process cannot access another process’s memory.

Methods:

- Base and limit registers
- Protection bits
- Access control mechanisms

Benefits:

- System stability
- Data security
- Error isolation

MEMORY SWAPPING

Swapping is the process of moving processes between main memory and disk.

- Inactive processes are swapped out to disk
- Active processes are swapped into memory

Purpose:

- Frees physical memory
- Enables execution of more processes

Swapping is a key component of **virtual memory**.

VIRTUAL MEMORY

Virtual Memory allows programs to use more memory than physically available.

Key features:

- Uses disk as an extension of RAM
- Only required portions of a program are loaded into memory
- Improves multitasking capability

MEMORY MAPPING

Memory Mapping translates virtual addresses to physical addresses.

Performed using:

- Page tables
- Memory Management Unit (MMU)

Advantages:

- Transparent to users
- Efficient memory access
- Supports virtual memory

MEMORY FRAGMENTATION

Fragmentation occurs when memory is broken into small unusable pieces.

Types:

- Internal Fragmentation
- External Fragmentation

Impact:

- Wastage of memory
- Difficulty in allocating large blocks

MEMORY COMPACTION

Memory Compaction is a technique to reduce external fragmentation.

- Moves processes to make free memory contiguous
- Improves memory utilization
- Time-consuming operation

MEMORY PAGING

Paging divides memory into fixed-size units called pages.

Components:

- Pages (virtual memory)
- Frames (physical memory)
- Page table

Benefits:

- Eliminates external fragmentation
- Efficient handling of large memory

PAGE TABLE

A **Page Table** stores the mapping between:

- Virtual page numbers
- Physical frame numbers Used by:
- Memory Management Unit (MMU) Essential for address translation in paging systems.

MEMORY PROTECTION

- Memory protection is required to prevent:
  - One process from accessing another process’s memory
  - User processes from modifying operating system memory

RELOCATION AND LIMIT REGISTERS

- Protection can be provided using:
  - **Relocation register**
  - **Limit register**

RELOCATION REGISTER

- Contains:
  - The value of the **smallest physical address**
- Example:
  - Relocation register = **100040**

LIMIT REGISTER

- Contains:
    - The **range of logical addresses**
- Example:
    - Limit register = **74600**
- Logical addresses must be **less than the limit value**

ADDRESS VALIDATION

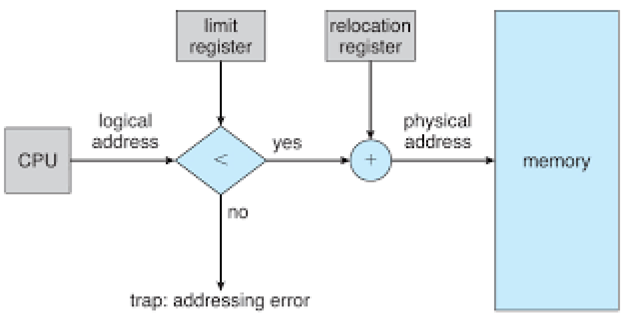
- Every logical address generated by the CPU is:
  - Checked against the **limit register**
- If the logical address exceeds the limit:
  - A protection fault occurs

ADDRESS MAPPING BY MMU

- If the logical address is valid:
    - The **Memory Management Unit (MMU)** maps it
- Mapping is done by:
    - Adding the logical address to the relocation register
- Mapped (physical) address is sent to memory

ROLE OF MMU

- MMU performs:
  - Dynamic address translation
- Ensures:
  - Processes access only their allocated memory region


limit register
relocation register
CPU
logical address
<
yes
+
physical address
memory
no
trap: addressing error

DISPATCHER AND CONTEXT SWITCH

- When the CPU scheduler selects a process:
  - The dispatcher performs a context switch
- During context switch:
  - Relocation register is loaded
  - Limit register is loaded
- Values correspond to the selected process

PROTECTION BENEFITS

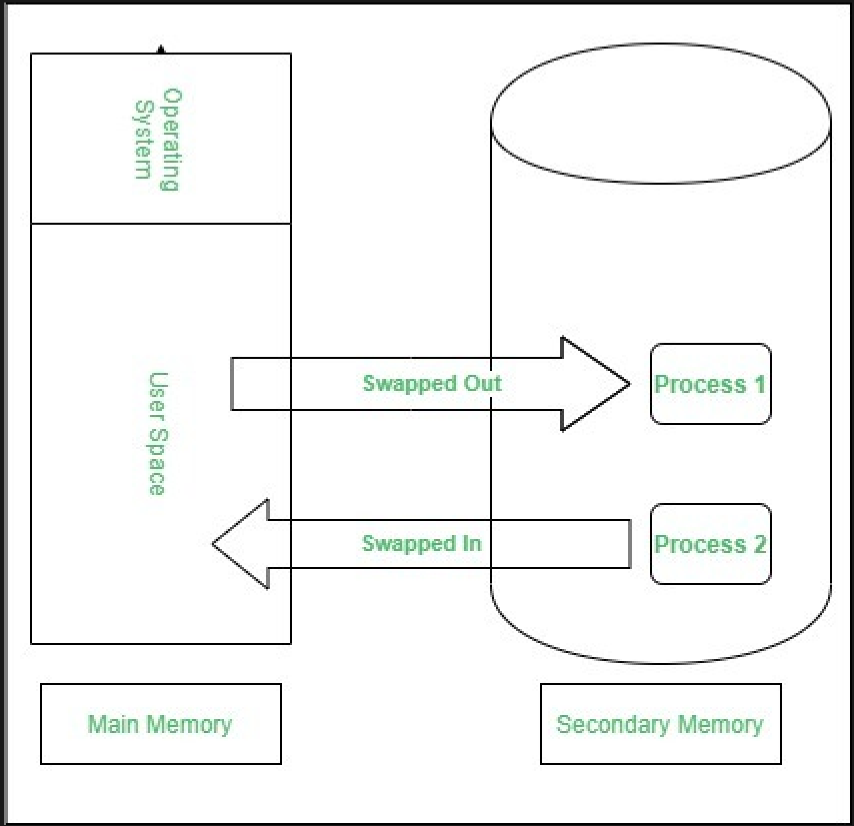
- Every CPU-generated address is checked
- Ensures protection of:
  - Operating system memory
  - Other users’ programs and data
- Prevents illegal memory access

DYNAMIC OS SIZE SUPPORT

- Relocation-register scheme allows:
  - Operating system size to change dynamically
- No need to fix OS memory location permanently

SWAPPING

- Swapping is a memory management technique used by the operating system
- A process must be in memory to be executed
- Swapping allows processes to be temporarily moved out of main memory to disk


Operating System
User Space
Swapped Out
Swapped In
Process 1
Process 2
Main Memory
Secondary Memory

SWAPPING AND PRIORITY-BASED SCHEDULING

- A variant of swapping is used in **priority-based scheduling algorithms**
- If a **higher-priority process** arrives:

- The OS swaps out a **lower-priority process**
    - Loads and executes the higher-priority process
- After completion:
    - The lower-priority process is swapped back in
    - Execution resumes from where it stopped

ROLL OUT AND ROLL IN

- This priority-based swapping technique is called:
  - **Roll out** → swapping a process out of memory
  - **Roll in** → swapping a process back into memory
- Commonly used in systems with limited memory

MEMORY SPACE AND SWAPPING

- Normally, a swapped-out process is brought back into:
  - The **same memory space** it previously occupied
- This restriction depends on the **address binding method**

ADDRESS BINDING AND SWAPPING

- **Assembly-time or Load-time binding**
  - Physical addresses are fixed
  - Process **cannot be moved** to a different memory location

- **Execution-time binding**
    - Physical addresses computed at runtime
    - Process **can be swapped into a different memory space**

BACKING STORE

- Swapping requires a **backing store**
- Usually implemented using a **fast disk**
- Requirements:
  - Large enough to store memory images of all users
  - Must support **direct access** to memory images

READY QUEUE AND PROCESS STATES

- The system maintains a **ready queue**
- Contains processes that are:
  - In memory, or
  - On the backing store
- All processes in the ready queue are ready to execute

ROLE OF THE DISPATCHER

- The CPU scheduler selects a process
- The dispatcher checks:
    - Whether the selected process is in memory
- If not in memory and no free space exists:

- A process currently in memory is swapped out
    - The required process is swapped in
- Registers are reloaded and control is transferred

CONTEXT SWITCH TIME IN SWAPPING

- Context-switch time in a swapping system is **high**
- Dominated by disk I/O operations
- Swap time significantly affects system performance

SWAP TIME EXAMPLE (GIVEN VALUES)

Assumptions:

- Process size: **1 MB**
- Disk transfer rate: **5 MB/s**

Calculation:

- Transfer time = 1000 KB / 5000 KB per second
- = 1 / 5 second
- = **200 milliseconds**

TOTAL SWAP TIME CALCULATION

- Average disk latency: **8 milliseconds**
- Time for one swap (in or out):
  - 200 ms + 8 ms = **208 milliseconds**
- Since both swap out and swap in are required:
  - Total swap time = **416 milliseconds**

IMPACT ON CPU SCHEDULING

- High swap time reduces CPU efficiency
- For efficient CPU utilization:
    - Execution time must be **much larger than swap time**

SWAPPING AND ROUND-ROBIN SCHEDULING

- In **round-robin scheduling**:
  - Time quantum should be significantly larger than swap time
- Given swap time ≈ **0.416 seconds**
- Time quantum must be **greater than 0.416 seconds**

CONTIGUOUS MEMORY ALLOCATION

- Main memory must accommodate:
  - The operating system
  - Multiple user processes
- Memory is typically divided into:
  - One partition for the resident OS
  - One partition for user processes

PLACEMENT OF THE OPERATING SYSTEM

- The operating system may be placed in:
  - Low memory, or
  - High memory
- The major factor affecting this decision:
  - Location of the **interrupt vector**
- Since interrupt vectors are usually in low memory:
  - The OS is commonly placed in **low memory**

NEED FOR MULTIPROGRAMMING

- Multiple user processes should reside in memory simultaneously
- This improves CPU utilization
- Memory must be allocated to processes waiting in the **input queue**

CONTIGUOUS MEMORY ALLOCATION CONCEPT

- Each process is allocated:
  - A **single contiguous block** of memory
- A process must fit entirely within one memory region

FIXED-SIZE PARTITIONING

- One of the simplest memory allocation techniques
- Memory is divided into:
  - Several **fixed-size partitions**
- Each partition can hold:
  - Exactly one process
- Degree of multiprogramming:
  - Limited by the number of partitions

MULTIPLE-PARTITION METHOD

- When a partition is free:
  - A process from the input queue is loaded into it
- When a process terminates:
  - The partition becomes available for reuse
- The OS maintains:
  - A table of free and occupied memory partitions

PROCESS LIFE CYCLE IN MEMORY

- Processes enter the system and wait in an **input queue**
- When memory is allocated:
  - Process is loaded into memory
  - Process competes for CPU time
- When a process terminates:
  - Memory is released
  - Space can be reassigned to another process

DYNAMIC MEMORY AND HOLES

- Free memory areas are called **holes**
- Holes vary in size and are scattered throughout memory
- When a process arrives:
  - The OS searches for a hole large enough

HOLE SPLITTING

- If a hole is larger than required:
  - It is split into two parts:
    - One allocated to the process
    - One returned to the set of holes

HOLE MERGING

- When a process releases memory:
  - The block becomes a new hole
- If adjacent holes exist:
  - They are merged into one larger hole

DYNAMIC STORAGE ALLOCATION PROBLEM

- The problem of:
  - Satisfying a request of size *n*
  - From a list of free holes
- This is known as:
  - **Dynamic storage allocation**

MEMORY ALLOCATION STRATEGIES

- The OS selects an appropriate hole using:
  - First Fit
  - Best Fit
  - Worst Fit

FIRST FIT STRATEGY

- Allocates:
  - The first hole that is large enough
- Search may begin:
  - From the beginning of the hole list, or
  - From where the last search ended
- Search stops once a suitable hole is found
- Generally faster than other methods

BEST FIT STRATEGY

- Allocates:
  - The smallest hole that is large enough
- Requires:
  - Searching the entire list (unless sorted by size)
- Produces:
  - The smallest leftover hole

WORST FIT STRATEGY

- Allocates:
  - The largest available hole
- Requires:
  - Searching the entire list (unless sorted)
- Produces:
  - The largest leftover hole

COMPARISON OF FIT STRATEGIES

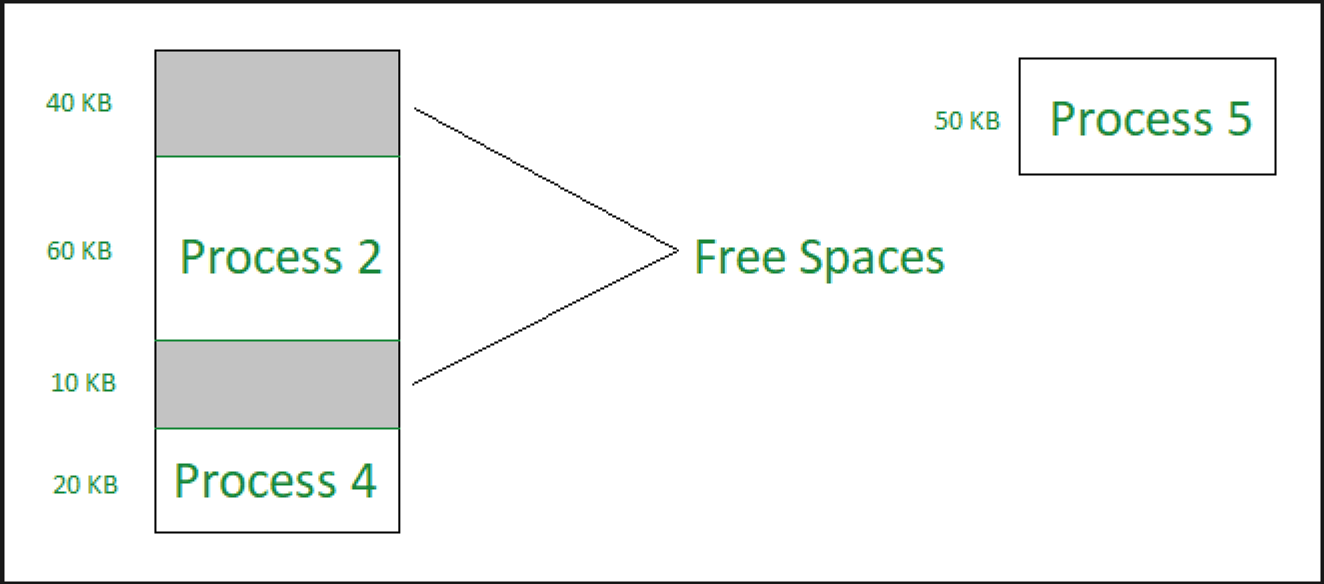
- Simulations show:
  - First fit and best fit outperform worst fit
- In terms of storage utilization:
  - First fit ≈ Best fit
- In terms of speed:
  - First fit is generally faster

FRAGMENTATION

- Memory fragmentation occurs when memory is wasted or inefficiently used
- Fragmentation can be:
  - **Internal fragmentation**
  - **External fragmentation**

EXTERNAL FRAGMENTATION

- External fragmentation exists when:
  - Enough total memory is available
  - Memory is **not contiguous**
- Free memory is broken into:
  - Many small holes


40 KB
60 KB
10 KB
20 KB
Process 2
Process 4
Free Spaces
50 KB
Process 5

WORST-CASE EXTERNAL FRAGMENTATION

- In the worst case:
  - A small free block exists between every two processes
- Although total free memory is sufficient:
  - It cannot be used effectively
- If all free memory were in one block:
  - Several more processes could be executed

COMPACTION

- **Compaction** is a solution to external fragmentation
- Goal:
  - Shuffle memory contents
  - Combine all free memory into one large block

CONDITIONS FOR COMPACTION

- Compaction is **not always possible**
- If relocation is:
  - **Static** (assembly-time or load-time)
    - Compaction cannot be done
  - **Dynamic** (execution-time)
    - Compaction is possible

DYNAMIC RELOCATION AND COMPACTION

- With dynamic relocation:
  - Programs and data are moved in memory
  - Base (relocation) register is updated
- No need to change logical addresses in the program

COST OF COMPACTION

- Cost of compaction must be considered
- Simplest compaction algorithm:
  - Move all processes toward one end of memory
  - Move all holes toward the other end
- Result:
  - One large free memory block
- Drawback:
  - Can be expensive in time and overhead

NONCONTIGUOUS MEMORY ALLOCATION

- Another solution to external fragmentation:
  - Allow a process's logical address space to be **noncontiguous**
- Physical memory can be allocated:
  - Wherever space is available

PAGING AND SEGMENTATION

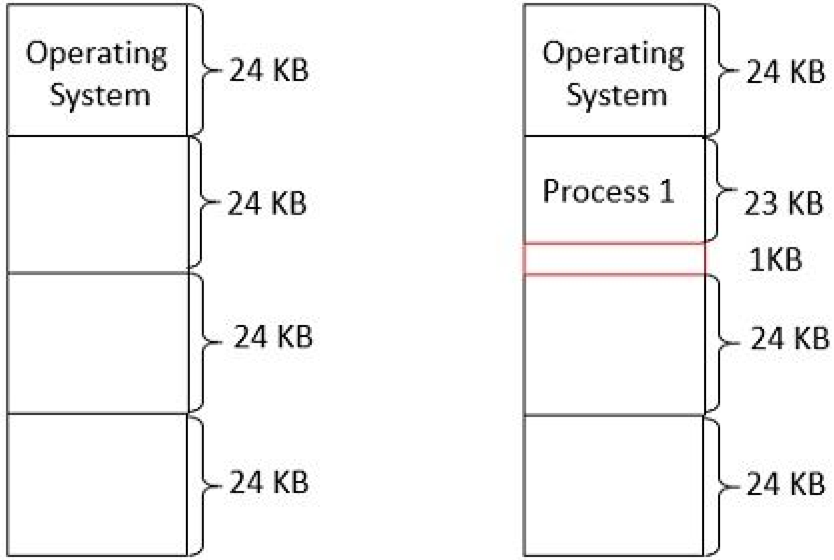
- Two complementary techniques support noncontiguous allocation:
  - **Paging**
  - **Segmentation**
- Paging and segmentation:
  - Reduce or eliminate external fragmentation
  - Can be used together

INTERNAL FRAGMENTATION

- Internal fragmentation occurs when:
  - Allocated memory is slightly larger than requested
- The unused portion:
  - Lies **inside** the allocated partition
  - Cannot be used by other processes
- This unused space is called **internal fragmentation**

EXAMPLE OF INTERNAL FRAGMENTATION

- Consider a multiple-partition allocation scheme
- Available hole size: **18,464 bytes**
- Process requests: **18,462 bytes**
- If allocated exactly:
  - Remaining hole = **2 bytes**
- Problem:
  - Overhead of managing a 2-byte hole is greater than the hole itself



Example of Internal Fragmentation

SOLUTION APPROACH

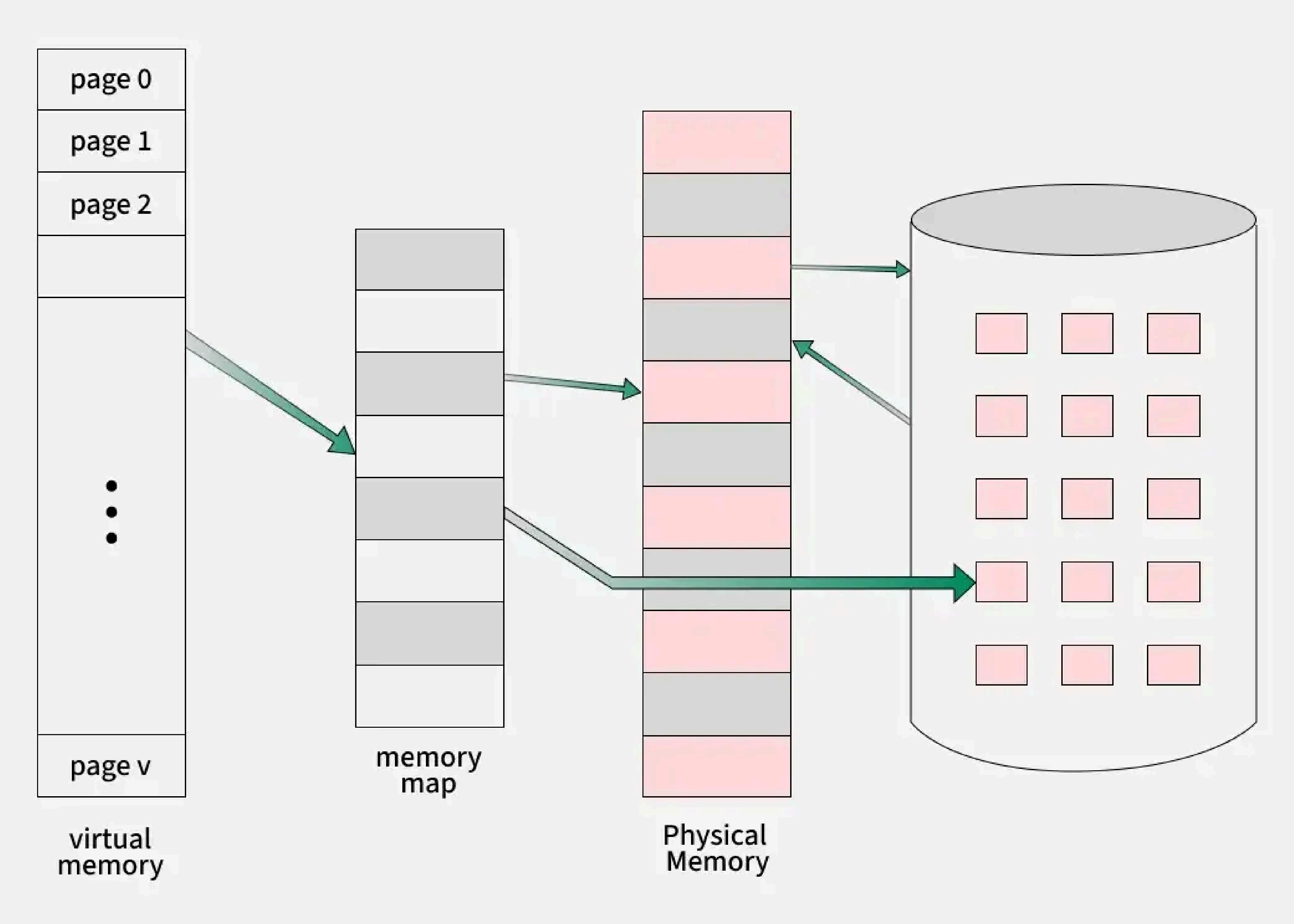
- Physical memory is divided into:
  - **Fixed-sized blocks**
- Memory is allocated in:
  - Units of block size
- This approach:
  - Simplifies allocation
  - Accepts some internal fragmentation to avoid excessive overhead

VIRTUAL MEMORY

- Virtual memory is a memory management technique that allows a computer to:
  - Use more memory than is physically available (RAM)
- When RAM is full:
  - Data is temporarily transferred to a hard drive or SSD
- This frees up RAM for active processes
- Data moved to storage can be retrieved when needed

- Managed entirely by the operating system
- Transparent to applications:
    - Programs behave as if full physical memory is available
- Advantages:
    - Allows more programs to run simultaneously
    - Supports larger data sets

- Limitations:
    - Disk access is slower than RAM
    - Excessive virtual memory use can cause:
        - Slow performance
        - System unresponsiveness
    - Heavy usage may fragment the disk, degrading performance further

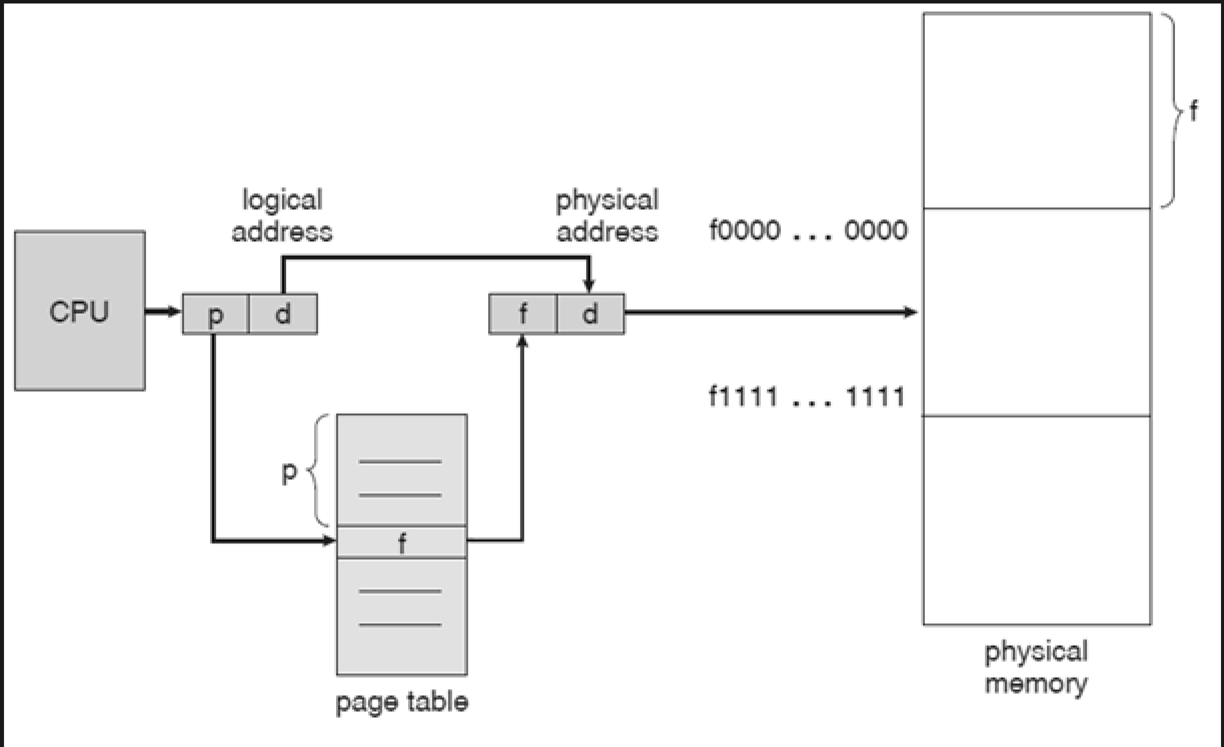

page 0
page 1
page 2
page v
virtual memory
memory map
Physical Memory

PAGING

- Paging is a memory-management scheme that allows:
  - The physical address space of a process to be **noncontiguous**
- Eliminates the need to fit variable-sized memory chunks into contiguous space
- Due to its advantages:
  - Paging is commonly used in modern operating systems

HARDWARE SUPPORT FOR PAGING

- Paging is supported directly by hardware
- Implemented on:
    - **64-bit microprocessors**
- Hardware assistance makes paging efficient and practical


logical
address
physical
address
CPU
p
d
f
d
f0000 ... 0000
f1111 ... 1111
f
p
f
page table
physical
memory

MEMORY DIVISION IN PAGING

- Physical memory is divided into:
  - Fixed-sized blocks called **frames**
- Logical (virtual) memory is divided into:
  - Fixed-sized blocks of the same size called **pages**

LOADING PAGES INTO MEMORY

- When a process is executed:
  - Its pages are loaded from the backing store
  - Pages can be placed into **any available memory frames**
- Contiguous allocation is not required

BACKING STORE STRUCTURE

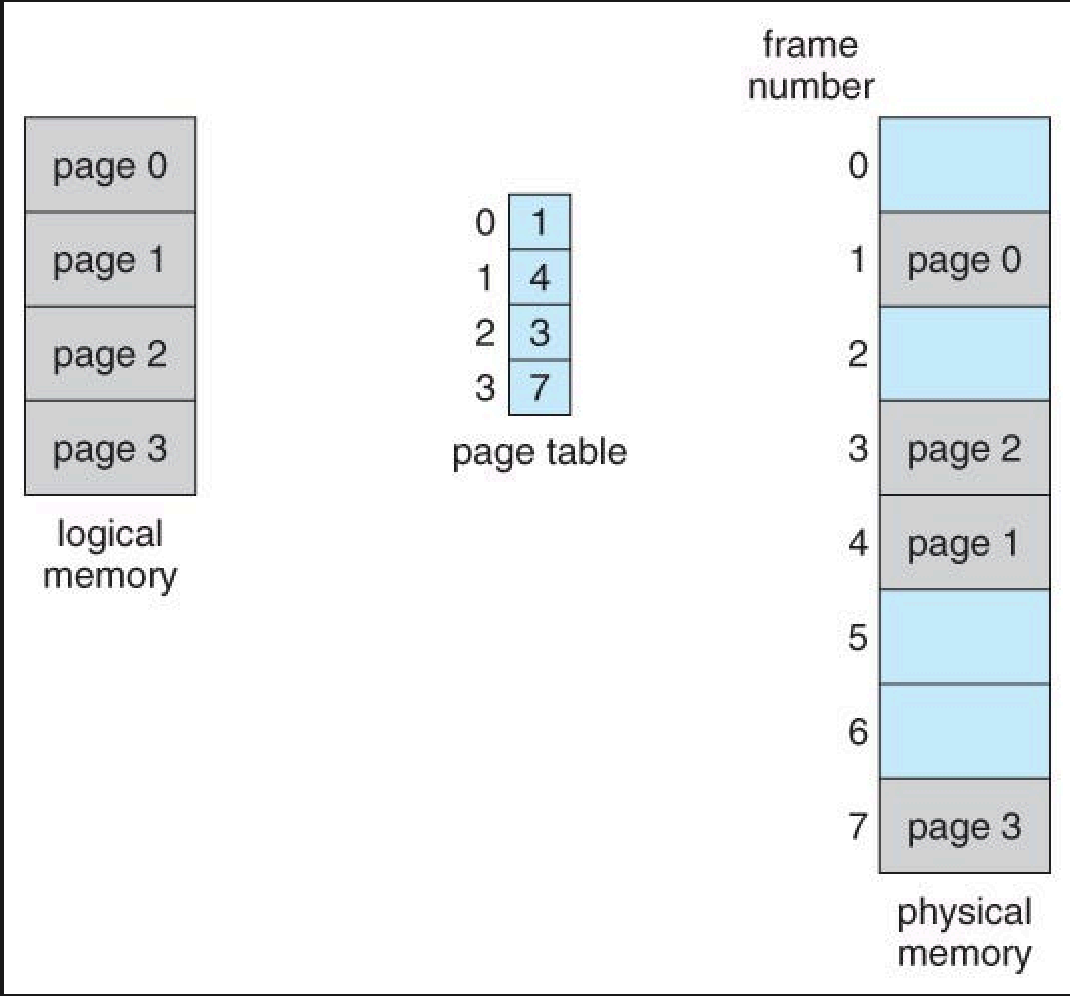
- The backing store is divided into:
  - Fixed-sized blocks
- These blocks are:
  - The same size as memory frames
- This simplifies paging operations

ADDRESS STRUCTURE IN PAGING

- Every CPU-generated address is divided into:
    - **Page number (p)**
    - **Page offset (d)**
- The page number is used to:
    - Index into the page table

PAGE TABLE

- The page table stores:
  - Base address of each page in physical memory
- Each entry maps:
  - A page number to a frame number


page 0
page 1
page 2
page 3
logical memory
0 1
1 4
2 3
3 7
page table
frame number
0
1 page 0
2
3 page 2
4 page 1
5
6
7 page 3
physical memory

ADDRESS TRANSLATION

- The physical address is formed by:
  - Combining the frame base address (from page table)
  - With the page offset
- This physical address is sent to:
  - The memory unit

- Page size is typically a **power of 2**
- Common page sizes range from:
    - **512 bytes to 16 MB**
- Most modern systems use:
    - **4 KB to 8 KB pages**
- Some systems support even larger page sizes

LOGICAL ADDRESS STRUCTURE

- If logical address space size = **2^m**
- Page size = **2^n** addressing units (bytes or words)
- Then:
  - High-order (**m − n**) bits → **page number (p)**
  - Low-order **n** bits → **page offset (d)**

LOGICAL ADDRESS REPRESENTATION

- Logical address format:
  - **< p , d >**
- Where:
  - **p** = index into the page table
  - **d** = displacement within the page

FRAGMENTATION IN PAGING

- Paging **eliminates external fragmentation**
- Any free frame can be allocated to any process
- Contiguous memory is not required

INTERNAL FRAGMENTATION IN PAGING

- Paging may cause **internal fragmentation**
- Occurs when:
  - Process size does not align with page boundaries
- The last frame may not be completely used

INTERNAL FRAGMENTATION EXAMPLE

- Page size: **2,048 bytes**
- Process size: **72,766 bytes**
- Pages required:
  - 35 full pages + 1,086 bytes
- Frames allocated:
  - 36 frames
- Internal fragmentation:
  - 2,048 − 1,086 = **962 bytes**

HARDWARE SUPPORT FOR PAGING

- Hardware support is required to implement page tables efficiently
- Page-table implementation can be done in several ways

PAGE TABLE USING REGISTERS

- Simplest implementation:
  - Page table stored in **dedicated registers**
- CPU dispatcher:
  - Reloads these registers during a context switch
- Suitable when:
  - Page table is reasonably small
  - Example: **256 entries**
- Advantage:
  - Very fast access

LARGE PAGE TABLES IN MODERN SYSTEMS

- Contemporary systems support:
  - Very large page tables
  - Example: **up to 1 million entries**
- Using registers for such large tables:
  - Not feasible

PAGE TABLE IN MAIN MEMORY

- Page table is stored in:
  - **Main memory**
- A special register called:
  - **Page-Table Base Register (PTBR)**
  - Points to the page table
- Changing the page table:
  - Requires changing only the PTBR

PROBLEM WITH PTBR APPROACH

- Accessing a memory location requires:
    1. Accessing the page table using PTBR
    2. Accessing the actual memory location
- This results in:
    - **Two memory accesses per reference**
- Leads to slower memory access time

TRANSLATION LOOK-ASIDE BUFFER (TLB)

- Standard solution to reduce memory access time:
  - **Translation Look-Aside Buffer (TLB)**
- TLB is:
  - Small
  - Fast
  - Hardware cache

CHARACTERISTICS OF TLB

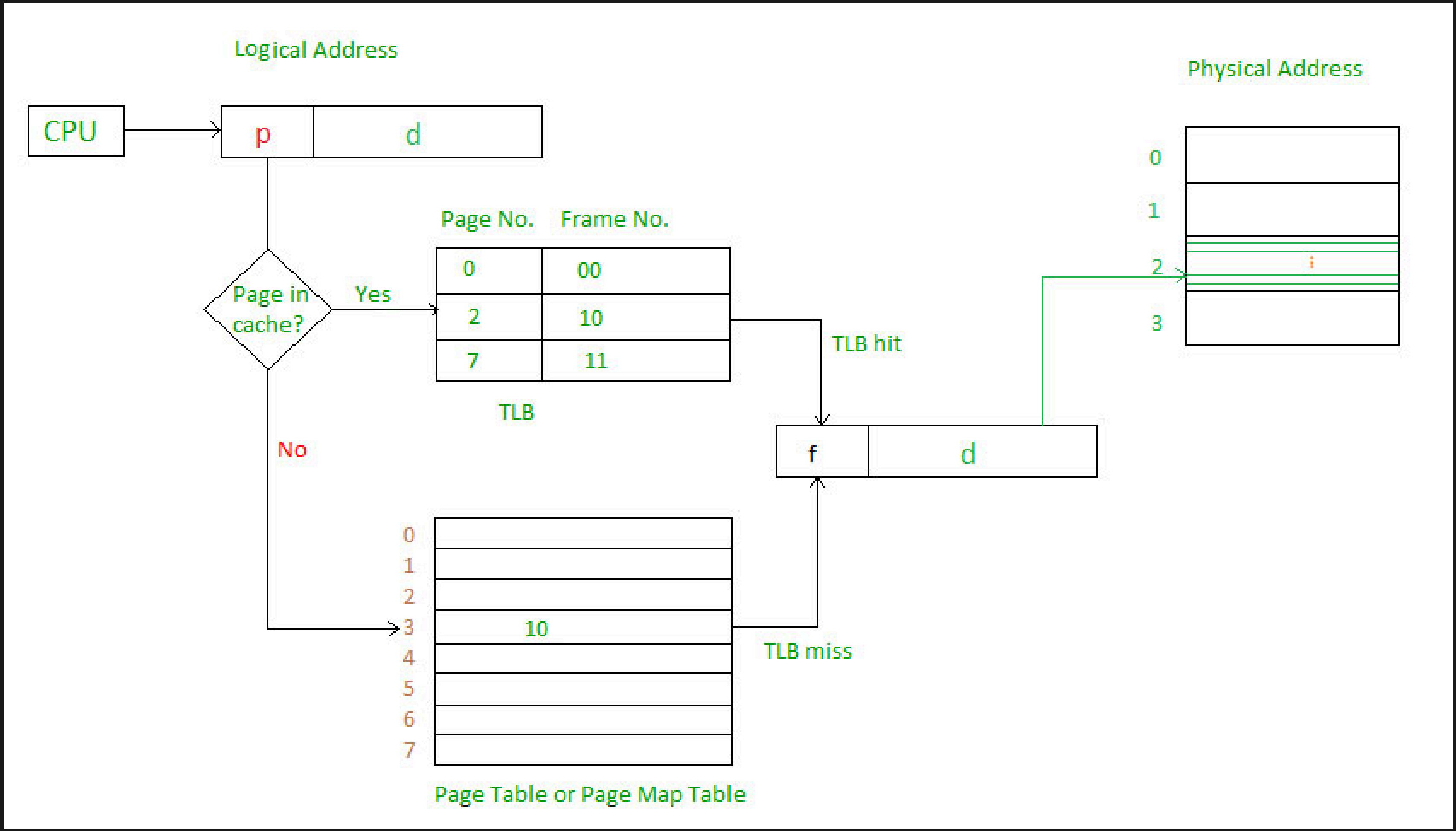
- TLB is:
  - **Associative, high-speed memory**
- Each TLB entry contains:
  - **Key (tag)** – page number
  - **Value** – frame number

TLB OPERATION

- When an address is presented:
  - It is compared with all TLB keys simultaneously
- If a match is found:
  - Corresponding frame number is returned
- Search operation:
  - Very fast
- Hardware cost:
  - High

TLB SIZE

- Number of TLB entries is limited
- Typical size:
  - **64 to 1,024 entries**
- Small size balances:
  - Speed
  - Hardware cost


Logical Address
CPU
p
d
Page No.
Frame No.
0
00
2
10
7
11
TLB
Page in cache?
Yes
No
TLB hit
f
d
Physical Address
0
1
2
3
0
1
2
3
10
4
5
6
7
TLB miss
Page Table or Page Map Table

SEGMENTATION – INTRODUCTION

- **Segmentation** is a memory management technique
- Memory is divided into **variable-sized segments**
- Each segment corresponds to a **logical unit** of a program
- Examples of segments:
  - Code segment
  - Stack
  - Heap
  - Data structures

PURPOSE OF SEGMENTATION

- Allows **dynamic memory allocation at runtime**
- Memory need not be allocated entirely at compile time
- Helps:
  - Reduce memory wastage
  - Improve utilization of available memory
- Matches programmer’s logical view of memory

SEGMENTED MEMORY SYSTEM

- Each segment is assigned:
  - A **Segment Identifier (SID)**
  - A **base address**
- Base address:
  - Indicates the first byte of the segment in physical memory

MEMORY ALLOCATION IN SEGMENTATION

- When a program requests memory:
  - OS allocates a segment of required size
  - Assigns a unique SID
  - Returns the base address to the program
- Segments can be allocated and deallocated dynamically

ADDRESSING IN SEGMENTATION

- Programs use **relative addressing**
- Address of a byte is calculated:
    - Relative to the base address of its segment
- Program does not need to know:
    - Absolute physical memory addresses
- Supports relocation during execution

LOGICAL ADDRESS STRUCTURE

- A logical address has two parts:
  - **Segment number (s)**
  - **Offset within the segment (d)**
- Format:
  - < s , d >

SEGMENT TABLE

- Segment number **s** is used as an index into the segment table
- Each segment table entry contains:
  - **Base address** of the segment
  - **Limit (length)** of the segment

ADDRESS VALIDATION AND MAPPING

- Offset **d** must satisfy:
  - `0 ≤ d < segment limit`
- If valid:
  - Physical address = segment base + offset
- If invalid:
  - Trap to the operating system

EXAMPLE: SEGMENT MAPPING

- Five segments numbered **0 to 4**
- Segment table contains base and limit for each segment

EXAMPLE CALCULATIONS

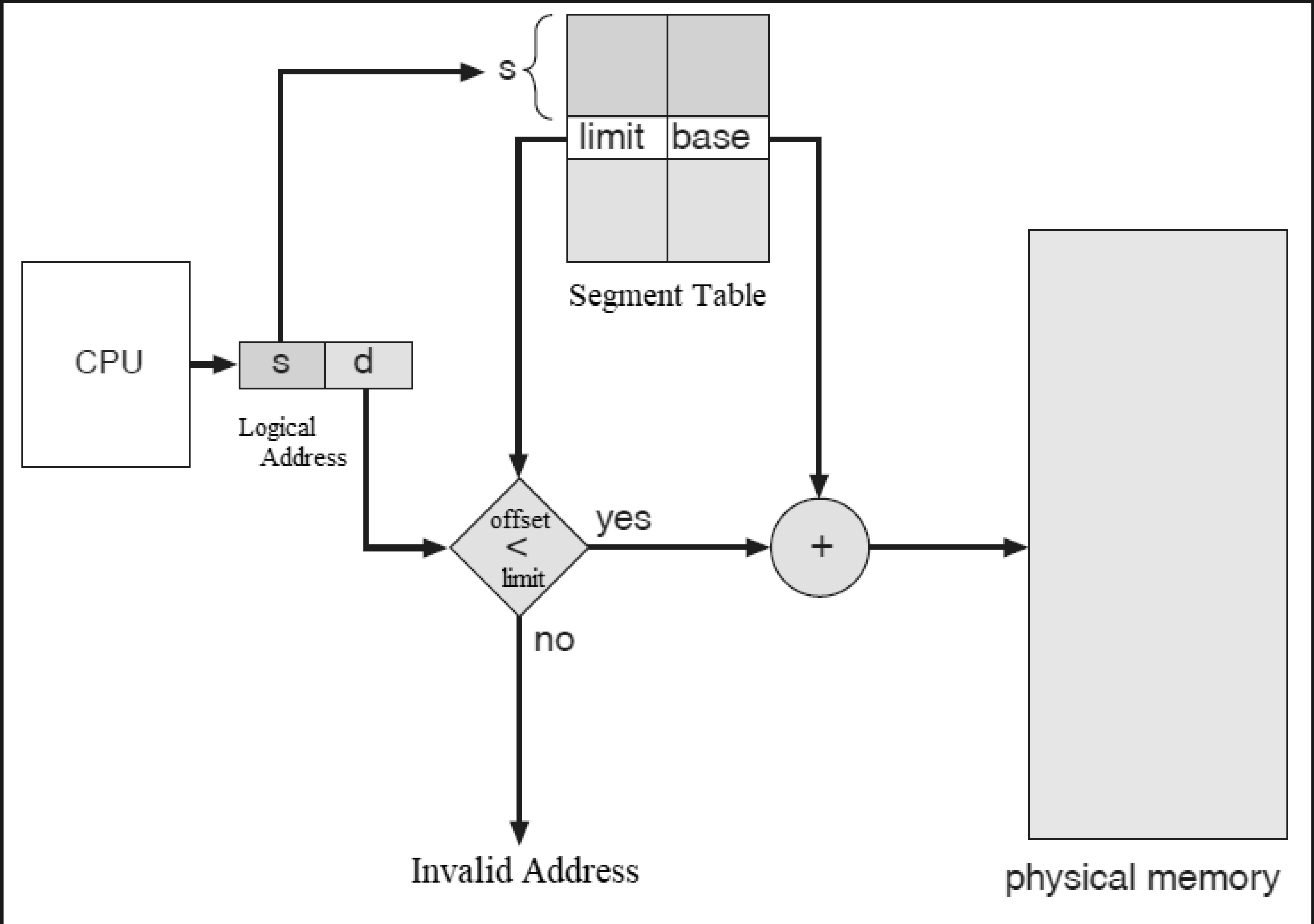
- Segment 2:
    - Base = 4300
    - Length = 400 bytes
    - Reference to byte 53:
        - Physical address = 4300 + 53 = **4353**

MORE EXAMPLES

- Segment 3:
  - Base = 3200
  - Reference to byte 852:
    - Physical address = 3200 + 852 = **4052**

PROTECTION EXAMPLE

- Segment 0:
  - Length = 1000 bytes
- Reference to byte 1222:
  - Offset exceeds segment limit
  - Results in a **trap to the operating system**


s
limit
base
Segment Table
CPU
s
d
Logical
Address
offset
<
limit
yes
+
no
Invalid Address
physical memory

VARIABLE PARTITION MEMORY ALLOCATION

- Variable partition memory allocation is a memory management technique
- Main memory is divided into **variable-sized partitions**
- Partitions are created dynamically based on program requirements
- Memory is allocated to programs **as needed**

CHARACTERISTICS OF VARIABLE PARTITIONING

- Partition sizes are not fixed
- Better utilization of memory compared to fixed partitions
- Can lead to fragmentation
- Commonly used allocation strategies determine efficiency

ALLOCATION ALGORITHMS

- Three main algorithms are used:
  - **First Fit**
  - **Worst Fit**
  - **Best Fit**
- These algorithms decide:
  - Which free partition (hole) should be allocated to a program

FIRST FIT ALGORITHM

- Operating system scans memory:
  - From the beginning
- Allocates:
  - The **first partition** large enough to hold the program
- Advantages:
  - Simple to implement
  - Fast execution
- Disadvantages:
  - Leaves small unused partitions
  - Causes memory fragmentation

WORST FIT ALGORITHM

- Operating system scans memory to find:
    - The **largest available partition**
- Allocates the program to this largest partition
- Objective:
    - Leave large free spaces for future allocations
- Disadvantages:
    - Causes significant fragmentation
    - May make future large allocations difficult

BEST FIT ALGORITHM

- Operating system scans memory to find:
  - The **smallest partition** that can hold the program
- Objective:
  - Minimize wasted memory
- Advantages:
  - Reduces unused space in allocated partitions
- Disadvantages:
  - Creates many small unused partitions
  - Leads to fragmentation

COMPARISON SUMMARY

- First Fit:
  - Fast and simple
  - Moderate fragmentation
- Best Fit:
  - Minimizes wasted space
  - High external fragmentation
- Worst Fit:
  - Attempts to preserve large holes
  - Usually poorest performance

PAGE FAULT – DEFINITION

- A **page fault** is an exception that occurs when:
  - A program tries to access a page
  - That page is **not present in physical memory**
- The required page is outside the current working set

PAGE FAULT IN VIRTUAL MEMORY

- Virtual memory allows programs to:
  - Use more memory than physically available
- Pages are:
  - Swapped in and out of physical memory as needed
- When a required page is not in memory:
  - A page fault occurs

PAGE FAULT HANDLING

- On a page fault, the operating system:
  - Checks whether the page is in physical memory
- If the page is not present:
  - OS selects a page to evict using a **page replacement algorithm**
  - Frees space for the required page

PAGE SWAPPING PROCESS

- The requested page is:
  - Loaded from secondary storage (disk/SSD)
- This process is called:
  - **Page swapping** or **page fault handling**
- Once loaded:
  - Program execution resumes normally

PERFORMANCE IMPACT

- Page faults degrade performance because:
  - Disk access is much slower than RAM access
- Excessive page faults can:
  - Slow down programs
  - Reduce system responsiveness

IMPORTANCE OF REDUCING PAGE FAULTS

- Minimizing page faults is a key goal of:
  - Operating system design
  - Memory management strategies
- Efficient page replacement improves:
  - System performance
  - User experience

PAGE REPLACEMENT ALGORITHMS

- **First In First Out (FIFO)** – Replaces the page that has been in memory the longest.
- **Least Recently Used (LRU)** – Replaces the page that has not been used for the longest time.
- **Optimal Page Replacement** – Replaces the page that will not be used for the longest period in the future.

FIRST-IN-FIRST-OUT (FIFO) PAGE REPLACEMENT

- FIFO is a basic page replacement algorithm used in operating systems
- It follows the principle:
  - The page that was **first brought into memory** is the **first to be replaced**
- Replacement occurs when:
  - A page fault happens
  - No free page frame is available

FIFO WORKING AND LIMITATION

- The OS maintains:
    - A **queue** of page frames for a process
- New pages are:
    - Added to the **end of the queue**
- When frames are full:
    - The page at the **front of the queue** is replaced

- Advantages:
  - Simple
  - Easy to implement
- Limitation:
  - Suffers from **Belady’s Anomaly**
  - Increasing page frames may increase page faults

LEAST RECENTLY USED (LRU) PAGE REPLACEMENT ALGORITHM

- LRU is a widely used page replacement algorithm
- It replaces the page that has been **least recently used**
- When a page fault occurs:
  - The OS must select a page in memory for replacement
- LRU assumes:
  - Pages used recently are likely to be used again soon

WORKING, ADVANTAGES, AND LIMITATIONS OF LRU

- OS maintains a list of pages currently in memory
- On every page access:
  - The page is moved to the **front of the list**
- Page replacement:
  - The page at the **back of the list** (least recently used) is removed

- Advantages:
  - Keeps frequently used pages in memory
  - Performs well in practice
- Limitations:
  - Expensive to implement in hardware
  - Requires updating the list on every access
  - May perform poorly for programs with large, rapid data access
- Improvements:
  - Modified versions like **Clock** or **Second Chance** algorithms are used

OPTIMAL PAGE REPLACEMENT ALGORITHM

- Optimal Page Replacement is an ideal page replacement algorithm
- It replaces the page that will **not be used for the longest time in the future**
- Requires knowledge of **future page references**
- Not practical for real operating systems

PURPOSE AND WORKING OF OPTIMAL ALGORITHM

- Used as a **theoretical upper bound** for comparison
- Other algorithms are evaluated by comparing their page faults with optimal
- Implementation (simulation):
  - Scan the entire page reference sequence
  - For each page, determine time until next use

- Replace the page with the **maximum future use time**
  - If a page is never referenced again, use end of sequence as reference
- Useful for:
  - Performance analysis
  - Benchmarking page replacement algorithms

DISK STRUCTURE

- Disk structure defines how data is **organized and stored** on a storage device
- Determines how data is **stored, accessed, and protected**
- Essential for efficient data management and system performance

FILE SYSTEM

- Most common disk structure
- Organizes data into **files and directories (folders)**
- Manages:
  - Disk space allocation
  - File locations
  - Access permissions
- Enables operating systems and applications to access data

TYPES OF FILE SYSTEMS

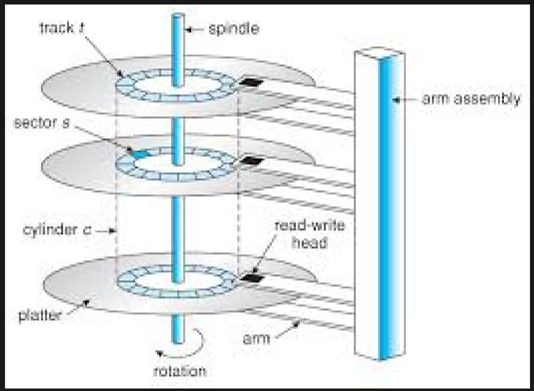
- Different operating systems use different file systems:
  - **NTFS** – Windows
  - **HFS+** – macOS
  - **ext4** – Linux
- Some file systems are designed for specific uses
  - Example: **FAT** for removable storage devices

DISK PARTITIONS

- Disk can be divided into multiple **partitions**
- Partition tables define:
  - Size of each partition
  - Location on disk
- Each partition can have its own file system

BOOT RECORDS AND IMPORTANCE

- **Boot records** store information needed to start the operating system
- Loaded when the computer powers on
- Disk structures ensure:
  - Proper system startup
  - Data reliability
  - Protection against data corruption



track t
spindle
arm assembly
sector s
cylinder c
read-write
head
platter
arm
rotation

Category	Details
Platter Size (Historical Range)	0.85” to 14”
Common Platter Sizes	3.5”, 2.5”, 1.8”
Storage Capacity	30 GB to 3 TB per drive
Theoretical Transfer Rate	6 Gb/sec
Effective Transfer Rate	~1 Gb/sec
Seek Time Range	3 ms to 12 ms

Typical Desktop Seek Time	**~9 ms**
Average Seek Time Basis	Measured or calculated using 1/3 of total tracks
Latency Dependency	Based on spindle (RPM) speed
Latency Formula	Latency = 60 / RPM
Average Latency	½ × (60 / RPM)

DISK ADDRESSING AND LOGICAL BLOCK MAPPING

- Disk drives are addressed as large **1-dimensional arrays of logical blocks**
- A **logical block** is the smallest unit of data transfer
- **Low-level formatting** creates logical blocks on the physical disk
- Logical blocks are mapped **sequentially to disk sectors**
- **Sector 0** is the first sector of the first track on the **outermost cylinder**

- Mapping proceeds:
  - Through the current track
  - Then remaining tracks of the same cylinder
  - Then inward cylinder by cylinder
- Logical-to-physical address mapping is generally simple
- **Bad sectors** complicate address mapping
- Number of sectors per track may be **non-constant** due to **constant angular velocity (CAV)**

DISK SCHEDULING

- The operating system is responsible for using disk hardware efficiently
- Main goals:
  - Fast access time
  - High disk bandwidth
- Disk scheduling focuses on **minimizing seek time**
- Seek time is approximately proportional to **seek distance**

DISK I/O REQUESTS AND BANDWIDTH

- Disk bandwidth = total bytes transferred ÷ total time from first request to last completion
- Disk I/O requests can originate from:
  - Operating system
  - System processes
  - User processes

- Each I/O request includes:
  - Input or output mode
  - Disk address
  - Memory address
  - Number of sectors to transfer

REQUEST QUEUES AND SCHEDULING NEED

- The OS maintains a **queue of disk I/O requests** for each disk or device
- If the disk is idle, it can immediately service a request
- If the disk is busy, new requests are queued
- Disk scheduling and optimization algorithms are meaningful **only when a request queue exists**

ROTATIONAL LATENCY

- Rotational latency is the delay experienced while the **disk rotates** to position the read/write head over the desired sector
- The read/write head must **wait for the correct sector** to pass underneath
- Determined by **disk rotational speed** (RPM)
- Important factor in HDD performance and **data access time**

ROTATIONAL LATENCY – CALCULATION AND OPTIMIZATION

- **Average rotational latency** = ½ × time for one full disk rotation
- Total **access time** = Average seek time + Average rotational latency
- Reducing rotational latency improves performance:
  - Increase **rotational speed**
  - Use disks with **larger capacity**
  - Use **SSDs**, which eliminate rotational latency

SEEK TIME

- Seek time is the time required for a hard disk's **read/write head** to move to the track containing the desired data
- Measures how quickly the head can position itself over the correct location on the disk
- Critical factor in **disk performance and access speed**

SEEK TIME – MEASUREMENT AND IMPORTANCE

- Typically measured in **milliseconds (ms)**
- Lower seek times are better for **faster data retrieval**
- Varies depending on **hard drive model and design**
- Directly affects the **efficiency of data access and transfer**

ROTATIONAL LATENCY & SEEK TIME – NUMERICAL EXAMPLE

- To calculate rotational latency and seek time, you need:
  - **Rotational speed** of the disk (RPM)
  - **Average seek time** (ms)
  - **Distance** the read/write head moves (tracks)

EXAMPLE HARD DISK SPECIFICATIONS

- Rotational speed: **7200 RPM**
- Average seek time: **8 ms**
- Distance to move read/write head: **3 tracks**
- Total tracks on disk: **16,384**

ROTATIONAL LATENCY CALCULATION

- Formula:
  `Rotational latency = 60 / (RPM × 2) ms`
- Calculation:
  `Rotational latency = 7200 / 60 / 2 = 60 / 2 = 30 ms`
- **Result:** Rotational latency = **30 ms**

SEEK TIME CALCULATION

- Formula:
  `Seek time = Average seek time × (Tracks moved / Total tracks)`
- Calculation:
  `Seek time = 8 × (3 / 16384) = 0.0147 ms`
- **Result:** Seek time = **0.0147 ms**

SCHEDULING ALGORITHMS

- FIFO - First come first served
- SSTF - Shortest seek time first
- SCAN
- C-SCAN
- C-LOOK Refer: os.surajgowda.in/disk-scheduling for simulation

DISK MANAGEMENT

- Disk Management is a **utility tool in Windows** for managing storage devices
- Allows users to **view partitions and volumes**
- Enables creation, formatting, deletion, and assignment of **drive letters**

DISK MANAGEMENT – PARTITION OPERATIONS

- Users can **extend, shrink, or move partitions**
- Helps **optimize disk space** and manage storage efficiently
- Supports conversion between disk types: **Basic** ↔ **Dynamic**

DISK MANAGEMENT – ADVANCED FEATURES

- Configure advanced settings:
  - **Mirrored volumes**
  - **RAID arrays**
- Useful for managing **multiple storage devices**
- Enhances **disk performance and organization**

RAID – REDUNDANT ARRAY OF INDEPENDENT DISKS

- RAID = Redundant Array of **Inexpensive Disks**
- Uses **multiple disk drives** to provide reliability via **redundancy**
- **Increases mean time to failure (MTTF)** of storage system

RELIABILITY FACTORS IN RAID

- **Mean Time to Repair (MTTR):** exposure time when another failure could cause data loss
- **Mean Time to Data Loss (MTDL):** depends on MTTF and MTTR
- Example:
  - Disk MTTF = 1,300,000 hours
  - MTTR = 10 hours
  - **MTDL = $100{,}000^2$ / (2 × 10) = 500 × 10^6 hours ≈ 57,000 years**

RAID – PERFORMANCE & IMPROVEMENTS

- Often combined with **NVRAM** to improve write performance
- Multiple disks can **work cooperatively** for better efficiency
- Enhances **reliability, performance, and fault tolerance**

DISK STRIPING AND RAID LEVELS

- **Disk striping:** uses a group of disks as a single storage unit
- **RAID** is organized into **six different levels**
- Improves both **performance** and **reliability** through redundancy

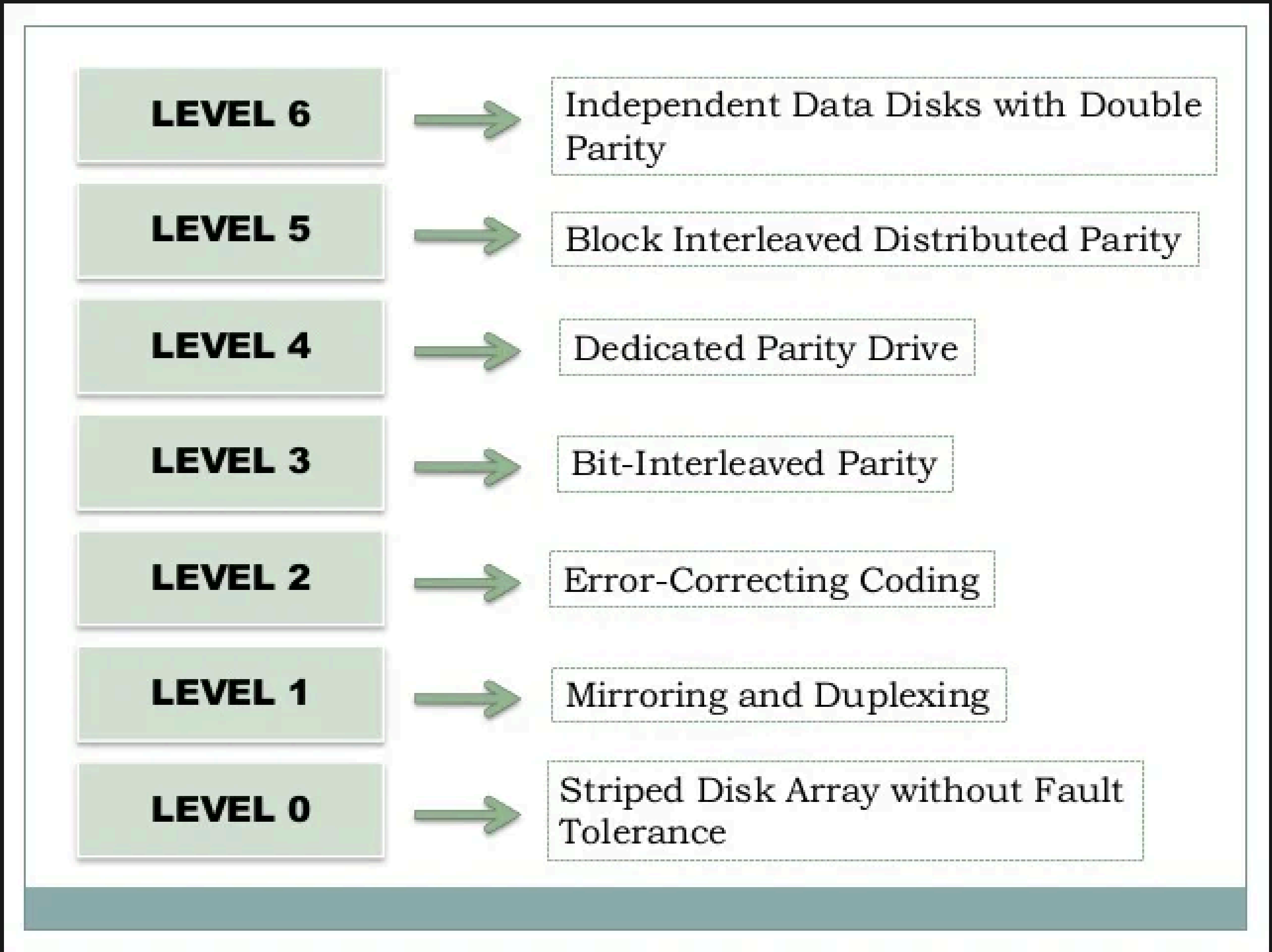
RAID MIRRORING AND STRIPES

- **RAID 1 – Mirroring/Shadowing:** keeps a duplicate of each disk
- **RAID 1+0 (Striped Mirrors) / 0+1 (Mirrored Stripes):** combines high performance and high reliability
- **RAID 4, 5, 6 – Block Interleaved Parity:** provides redundancy with **less storage overhead**

RAID ARRAY MANAGEMENT

- RAID within a single array can **still fail if the array fails**
- **Automatic replication** between arrays is common for added safety
- **Hot-spare disks:** unallocated disks that **replace failed disks automatically** and rebuild data

RAID LEVELS


LEVEL 6
Independent Data Disks with Double Parity
LEVEL 5
Block Interleaved Distributed Parity
LEVEL 4
Dedicated Parity Drive
LEVEL 3
Bit-Interleaved Parity
LEVEL 2
Error-Correcting Coding
LEVEL 1
Mirroring and Duplexing
LEVEL 0
Striped Disk Array without Fault Tolerance

Hewlett Packard Enterprise

BREAKDOWN OF COMMON RAID LEVELS

RAID LEVEL	METHOD	HARDWARE / SOFTWARE	MINIMUM # OF DISKS	COMMON USAGE	PROS	CONS
JBOD	SPANNING		2	INCREASE CAPACITY	COST-EFFECTIVE STORAGE	NO PERFORMANCE OR SECURITY BENEFITS
0	STRIPING		2	HEAVY READ OPERATIONS	HIGH PERFORMANCE (SPEED)	DATA IS LOST IF ONE DISK FAILS
1	MIRRORING		2	STANDARD APP SERVERS	FAULT TOLERANCE, HIGH READ PERFORMANCE	LAG FOR WRITE OPS, REDUCED STORAGE (BY 1/2)
5	STRIPING & PARITY		3	NORMAL FILE STORAGE & APP SERVERS	SPEED + FAULT TOLERANCE	LAG FOR WRITE OPS, REDUCED STORAGE (BY 1/3)
6	STRIPING & DOUBLE PARITY		4	LARGE FILE STORAGE & APP SERVERS	EXTRA LEVEL OF REDUNDANCY, HIGH READ PERFORMANCE	LOW WRITE PERFORMANCE, REDUCED STORAGE (BY 2/5)
10 (1+0)	STRIPING & MIRRORING		4	HIGHLY UTILIZED DATABASE SERVERS	WRITE PERFORMANCE + STRONG FAULT TOLERANCE	REDUCED STORAGE (1/2), LIMITED SCALABILITY

What Happened to 2-4 and 6-9?

The RAID levels described above are the most common levels used in enterprise scenarios. The levels in between are highly specialized and only make sense in very specific scenarios.

RAID 01 (RAID 0+1)

Mirror+ Stripe