

# Memory Management & Security

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## 3.1 Memory Allocation Techniques

Memory allocation strategies manage how processes obtain and use memory resources.

### **Fixed Partitioning:**

Divides physical memory into predetermined-size partitions.

Simple to implement.

Suffers from **internal fragmentation** (unused space within an allocated partition).

### **Variable Partitioning:**

Allocates memory blocks of exactly the required size to processes.

Eliminates internal fragmentation.

Creates **external fragmentation** over time (small free memory blocks scattered between allocated blocks).

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### **Paging:**

Divides both physical memory and process address spaces into fixed-size blocks. Physical memory blocks are called **frames**.

Process address space blocks are called **pages**.

Uses **page tables** for address translation (mapping logical pages to physical frames).

Enables efficient memory utilization.

Causes slight internal fragmentation (last page of a process may not be completely full).

### **Segmentation:**

Divides memory into logical units corresponding to program structure (e.g., code, data, stack segments).

More natural for programmers.

Complex to manage due to variable-sized segments, leading to external fragmentation.

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### **Modern Systems:**

Typically combine **paged segmentation**.

Uses segmentation for logical organization.

Uses paging for physical allocation.

## 3.2 Virtual Memory Implementation

Virtual memory creates the illusion of a memory space larger than physical RAM by storing inactive portions on secondary storage (like a disk).

### **Demand Paging:**

Loads pages into physical memory only when they are accessed (on demand).  
Reduces initial process load time and memory requirements.

### **Page Replacement Algorithms:**

Determine which page to evict from physical memory when a **page fault** occurs and no free frames are available.

### **First-In-First-Out (FIFO):**

Removes the oldest page (first page brought in).

Simple to implement.

Suffers from **Belady's anomaly** (increasing page frames can sometimes increase page faults).

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### **Optimal Algorithm:**

Replaces the page that will not be used for the longest period in the future.  
Impossible to implement practically (requires future knowledge).  
Serves as a benchmark for comparing other algorithms.

### **Least Recently Used (LRU):**

Replaces the page that has not been used for the longest time.  
Performance is close to optimal.  
Requires substantial hardware support to track usage.

### **Clock Algorithms:**

Approximate LRU performance with lower overhead.  
Use a **reference bit** (or use bit) to track page usage.

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### **Thrashing:**

Occurs when a system spends excessive time and resources on paging (swapping pages in and out) instead of executing useful work.

### **Addressed through:**

**Working Set Model:** Ensuring a process has its required set of pages in memory.

**Page Fault Frequency (PFF) Technique:** Adjusting the number of frames allocated based on the rate of page faults.

## 3.3 Memory Protection Mechanisms

Memory protection prevents processes from accessing unauthorized memory regions through hardware-enforced access rights.

### **Base and Limit Registers:**

Early protection mechanism.

Define each process's address space boundaries (a starting base address and a limit/range).

### **Page Table Entry Permission Bits:**

Control read, write, and execute access at the granularity of individual pages.

### **Buffer Overflow Attacks:**

Exploit software vulnerabilities to write data beyond the boundaries of an allocated buffer in memory.

Can overwrite return addresses to redirect program execution to malicious code.

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### **Stack Canaries:**

A defense against stack buffer overflows.

Place known values ("canaries") between buffers and control data (like return addresses) on the stack.

Check the integrity of the canary value before a function returns.

### **Non-executable Stack Protection:**

Marks stack memory as non-executable (NX bit).

Prevents execution of malicious code (shellcode) injected into the stack.

### **Address Space Layout Randomization (ASLR):**

Randomizes the memory locations of key areas (stack, heap, libraries) for each process.

Makes target addresses unpredictable for attackers.

These protections operate at multiple levels: hardware (Memory Management Units), operating system, and compiler.

## 3.4 Secure Memory Design Principles

Secure memory architectures implement isolation guarantees through hardware-enforced boundaries between security domains.

### **Virtualization-based Security:**

Uses hardware virtualization features (like hypervisors) to create strongly isolated containers for sensitive operations.

### **Trusted Execution Environments (TEEs):**

Provide hardware-protected, isolated areas for secure code execution and data processing.

Examples: **Intel SGX** (Software Guard Extensions) and **ARM TrustZone**.

### **Memory Encryption:**

Protects data confidentiality in memory, even from physical attacks.

Approaches range from **full memory encryption** to **selective encryption** of only sensitive regions.

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### **Memory Tagging:**

Associates metadata tags (a small number of bits) with each memory allocation or granule.

Used to detect spatial (out-of-bounds access) and temporal (use-after-free) safety violations.

### **Control-Flow Integrity (CFI) Techniques:**

Validate indirect control transfers (jumps, calls, returns) against a pre-determined, legitimate control-flow graph or policy.

Aims to prevent code reuse attacks (like ROP - Return-Oriented Programming).

These advanced mechanisms address sophisticated memory corruption attacks while aiming to maintain reasonable performance overhead.

1. <https://www.druva.com/glossary/what-is-a-disaster-recovery-plan-definition-and-related-faqs>
2. <https://www.konverge.co.in/virtualization-in-cloud-computing-need-types-and-importance/>
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