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BCA Honours | Semester III | Calicut University

Data Structures using C

Course Code: BCA3CJ201 • Module 1 Notes

MODULE I: INTRODUCTION TO DATA STRUCTURES, ARRAYS & LINKED LISTS

1. Foundational Data Structure Concepts

A data structure is a specialized format for organizing, processing, retrieving, and storing data in computer memory. An **Abstract Data Type (ADT)** is a mathematical model for data types where a data type is defined by its behavior (semantics) from the perspective of a user of the data, rather than by its concrete implementation.

- **Linear Data Structures:** Elements form a sequential sequence where each element (except the first and last) has a unique predecessor and successor (Arrays, Linked Lists, Stacks, Queues).
- **Non-Linear Data Structures:** Elements exhibit hierarchical or interconnected relationships (Trees, Graphs).

2. Arrays and Memory Address Calculation

An array is a collection of homogeneous elements stored in contiguous memory locations. For a 2D array $A[1..m, 1..n]$ with base address B and element size S bytes:

- **Row-Major Order:** $\text{Address}(A[i,j]) = B + S \times [(i-1) \times n + (j-1)]$
- **Column-Major Order:** $\text{Address}(A[i,j]) = B + S \times [(j-1) \times m + (i-1)]$

3. Linked Lists and Pointer Manipulation

A linked list is a dynamic linear data structure composed of nodes allocated at runtime via `malloc()`. Each node contains a data payload and a pointer linking to the subsequent node:

```
struct Node {
    int data;
    struct Node* next;
};
```

4. Illustrative Computational Working: Step-by-Step Numerical Example

Worked Numerical Example: 2D Array Memory Addressing & In-Place Linked List Reversal

Problem Statement:

1. A 2D floating-point matrix $M[1..5, 1..8]$ is stored in memory starting at base address $B = 4000$. Each floating-point number occupies $S = 4$ bytes.

Calculate the exact memory address of element $M[3, 5]$ under: (a) Row-Major Order, and (b) Column-Major Order.

2. Trace the step-by-step pointer manipulation algorithm to reverse a singly linked list in $O(n)$ time using three pointers: `prev`, `current`, and `next`.

Solution & Step-by-Step Working:

Part 1: 2D Array Address Calculations

Given parameters:

- Rows $m = 5$, Columns $n = 8$
- Target indices: $i = 3, j = 5$
- Base Address $B = 4000$, Element Size $S = 4$ bytes

(a) Row-Major Order Calculation:

In row-major order, all elements of row 1 and row 2 precede row 3. The number of complete rows preceding row 3 is $(i - 1) = 2$ rows, each containing $n = 8$ elements. In row 3, $(j - 1) = 4$ elements precede $M[3, 5]$.

$$\text{Offset} = [(i - 1) \times n + (j - 1)] = (2 \times 8) + 4 = 16 + 4 = 20 \text{ elements}$$

$$\text{Address}(M[3,5]) = B + (\text{Offset} \times S) = 4000 + (20 \times 4) = 4000 + 80 = \mathbf{4080}$$

(b) Column-Major Order Calculation:

In column-major order, all elements of columns 1 through 4 precede column 5. The number of complete columns preceding column 5 is $(j - 1) = 4$ columns, each containing $m = 5$ elements. In column 5, $(i - 1) = 2$ elements precede $M[3, 5]$.

$$\text{Offset} = [(j - 1) \times m + (i - 1)] = (4 \times 5) + 2 = 20 + 2 = 22 \text{ elements}$$

$$\text{Address}(M[3,5]) = B + (\text{Offset} \times S) = 4000 + (22 \times 4) = 4000 + 88 = \mathbf{4088}$$

Part 2: In-Place Singly Linked List Reversal Algorithm

Consider the linked list: `[10] -> [20] -> [30] -> NULL`.

The C algorithm maintains three pointer variables initialized as: `prev = NULL; current = head; next = NULL;`

```
while (current != NULL) {
    next = current->next;   // 1. Store successor node
    current->next = prev;   // 2. Reverse current node's pointer
    prev = current;         // 3. Advance prev pointer
    current = next;         // 4. Advance current pointer
}
head = prev;
```

Step-by-Step Execution Trace Table:

Iteration	`current`	`next`	`current->next` (Updated)	`prev` (Advanced)	`current` (Advanced)
Initial	[10]	NULL	→ [20]	NULL	[10]
Pass 1	[10]	[20]	→ NULL	[10]	[20]
Pass 2	[20]	[30]	→ [10]	[20]	[30]

Iteration	`current`	`next`	`current->next` (Updated)	`prev` (Advanced)	`current` (Advanced)
Pass 3	[30]	NULL	→ [20]	[30]	NULL

When `current == NULL`, the loop terminates. Setting `head = prev` yields the reversed list: `[30] -> [20] -> [10] -> NULL` in $O(n)$ time and $O(1)$ auxiliary space.

Advanced Architectural Extensions & Industrial Systems Synthesis

In contemporary enterprise software engineering and distributed computational infrastructure, mastering Data Structures using C demands a rigorous integration of foundational algorithms with large-scale production architectures. Systems operate in high-availability, low-latency environments where computational efficiency, cache locality, and provable system reliability govern operational success.

1. Contemporary Engineering Dilemmas and Architectural Solutions

Engineering teams designing systems centered around Data Structures using C must systematically navigate fundamental computational trade-offs:

- **Time Complexity Optimization versus Space Consumption:** In high-throughput algorithmic pipelines related to Arrays and Dynamic Memory, pre-computing intermediate lookup tables (memoization, spatial indices, hash tables) achieves near-instantaneous $O(1)$ query latency, but inflates physical memory footprints. Conversely, in-place algorithms minimize RAM utilization at the expense of higher cycle counts. Modern architectures dynamically calibrate memory allocations using memory-mapped I/O and cache-aware data layouts.
- **Concurrency Scalability versus Thread Contention:** While multi-core architectures allow massive horizontal execution, concurrent modifications to shared state structures create severe lock contention, thread synchronization bottlenecks, and cache line invalidation storms. High-performance frameworks deploy lock-free algorithms, optimistic concurrency control, and atomic compare-and-swap (CAS) primitives.
- **Algorithmic Determinism versus Real-World Heuristic Scalability:** Exact mathematical algorithms frequently encounter NP-hard combinatorial explosions as problem dimensions scale. Contemporary industrial systems bridge this gap by deploying bounded approximation algorithms and meta-heuristics that produce near-optimal solutions within guaranteed execution time windows.

2. Empirical Comparative Framework

A structured comparative assessment clarifies operational distinctions across conventional and modern paradigms in Data Structures using C:

Evaluation Dimension	Conventional Traditional Approach	Contemporary Integrated Paradigm	Strategic Impact Metric
Architecture Paradigm	Monolithic single-threaded architectures with tightly coupled state.	Distributed microservices with asynchronous event queues and thread-safe data structures.	Linear scalability and resilient fault isolation under peak transactional loads.
Data Processing	Synchronous batch processing characterized by	Real-time streaming pipelines (Apache Kafka, Flink) with sub-	Zero-latency decision intelligence and

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Pipeline	high latency and scheduled processing windows.	second event ingestion and processing.	immediate anomaly response.
Resilience & Failover	Manual failover mechanisms requiring operator intervention and scheduled downtime.	Automated self-healing clusters with dynamic health checking and zero-downtime rolling deployments.	Continuous availability meeting strict 99.999% Service Level Agreements (SLAs).
System Telemetry & Auditing	Static text logging with periodic post-incident analysis.	Distributed tracing (OpenTelemetry), structured JSON metrics, and automated root-cause diagnostics.	Mean Time to Detection (MTTD) and Recovery (MTTR) reduced from hours to seconds.

3. Step-by-Step Implementation and Operational Governance Roadmap

Executing enterprise-grade implementations of Data Structures using C requires an organized four-phase execution roadmap:

- **Phase I: Architectural Assessment & Baseline Telemetry:** Conducting diagnostic audits of baseline throughput, memory access patterns, and I/O bottlenecks to establish empirical performance benchmarks.
- **Phase II: Algorithmic Architecture & Prototype Modeling:** Formulating mathematically sound algorithmic workflows, defining abstract interfaces, and constructing modular proof-of-concept prototypes with automated unit tests.
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Industrial Risk Governance, Statutory Compliance & Failure Mode Analysis

Mission-critical systems must withstand rigorous scrutiny across operational, legal, and cyber-security dimensions. System architects deploy structured risk evaluation matrices to eliminate vulnerabilities across critical operational categories:

Risk Category	Primary Sources of Vulnerability	Diagnostic Warning Indicators	Mitigation Protocol & Internal Controls
Algorithmic & Logic Risk	Infinite recursion, stack overflows, unhandled edge cases, pointer corruption.	Core dumps, segmentation faults, abrupt memory footprint spikes, unresponsive threads.	Formal loop invariant assertions, strict boundary validation, automated fuzz testing, static code analysis.

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Statutory & Regulatory Risk	Non-compliance with national data protection regulations (DPDP Act, GDPR), audit trail gaps.	Unencrypted sensitive user data at rest, unlogged administrative data modifications.	Automated encryption (AES-256), immutable cryptographic audit logs, periodic external compliance audits.

Through systematic deployment of these engineering practices, rigorous mathematical modeling, and robust governance frameworks, modern computing professionals ensure the reliability, performance, and long-term resilience of critical digital infrastructure.

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