YZM2031

Data Structures and Algorithms

Week 2: Lists and Linked Lists

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Recap: Week 1

What We Covered

- C++ fundamentals and syntax
- Memory management (stack vs heap)
- Pointers and reference
- Classes and objects
- Object-oriented programming basics
- Templates

Today's Focus

Building on these concepts, we'll explore **Abstract Data Types** and our **first major data structure: Lists**

What is an Abstract Data Type (ADT)?

An **Abstract Data Type (ADT)** is a model that defines:

- **What** data can be stored
- **What** operations can be performed on that data
- **Not how** it's implemented

> Think of it as a **contract** or **interface** - it specifies *what* you can do, not *how* it's done.

Key Concept: Abstraction

Abstraction = Hiding implementation details, showing only functionality

- **What** you can do with a TV: change channels, adjust volume
- **How** it works internally: circuits, electronics (hidden)

ADT: The Contract vs Implementation

The Abstract Part (Interface)

What operations are available:

```
// List ADT Operations
- add(element)
- remove(element)
- get(index)
- size()
- isEmpty()
```

This is the CONTRACT:

- No mention of arrays
- No mention of pointers
- Just operations!

The Implementation Part

How we actually do it:

```
// Implementation 1: Array
class ArrayList {
    int* data;
    int size;
};

// Implementation 2: Linked List
class LinkedList {
    Node* head;
};
```

Same ADT, different implementations!

ADT in C++: Interface Example

```cpp
// ADT - defines WHAT, not HOW
class ListADT {
public:
    virtual void add(int value) = 0;
    virtual void remove(int value) = 0;
    virtual int get(int index) = 0;
    virtual int size() = 0;
    virtual bool isEmpty() = 0;
    virtual ~ListADT() {}
};

// Implementations
class ArrayList : public ListADT {
    // Implements using array
};

class LinkedList : public ListADT {
    // Implements using nodes and pointers
};
```

Users only see the interface, not the implementation!

Example: SumArray

Let's say we want to define an array which always sums up the value of items in it whenever we modify it.

```
class SumArray {
public:
    virtual int get(int) = 0;
    virtual void set(int, int) = 0;
    virtual int sum() = 0;
};
```

This is the ADT contract:

- Get value at index
- Set value at index
- Calculate sum of all elements

Example: SumArray

Implementation

```
class SumArrayImpl : public SumArray {
public:
    SumArrayImpl(int);
    int get(int);
    void set(int, int);
    int sum();
    ~SumArrayImpl();

private:
    int *array;
    int numElements;
};
```

Example: SumArray Implementation

Constructor

```
SumArrayImpl::SumArrayImpl(int n) {
    numElements = n;
    array = new int[n];
    for(int i = 0; i < n; i++)
        array[i] = 0;
}
```

Destructor

```
SumArrayImpl::~SumArrayImpl() {
    delete [] array;
}
```

Get & Set Functions

```
int SumArrayImpl::get(int index) {
    return array[index];
}

void SumArrayImpl::set(int index, int value) {
    array[index] = value;
}
```

Direct array access:

- Get: O(1) - constant time
- Set: O(1) - constant time

Example: SumArray Implementation

Sum Function

```
int SumArrayImpl::sum() {
    int sum = 0;
    for(int i = 0; i < n; i++)
        sum += array[i];
    return sum;
}
```

The Problem

We are going to call this sum function very frequently.
How can we make it more efficient?

The for loop is a performance bottleneck when sum() is called repeatedly!

Performance Analysis

Time Complexity

Operation	Complexity	Why?
`get(index)`	**O(1)**	Direct array access
`set(index, value)`	**O(1)**	Direct array access
`sum()`	**O(n)**	Loop through all elements

The Problem

If we call `sum()` **frequently**:

- Each call requires **n** operations
- For 1000 elements: 1000 operations per sum!
- For 1,000,000 elements: 1,000,000 operations per sum!

Can we do better? 🙋

Example: SumArray Implementation 2

Instead of calculating sum every time, maintain it!

```
class SumArrayImpl2 : public SumArray {
public:
    SumArrayImpl2(int);
    int get(int);
    void set(int, int);
    int sum();
    ~SumArrayImpl2();

private:
    int *array;
    int numElements;
    int theSum;      // NEW: Store the running sum
};
```

Trade-off: Use extra memory to save computation time

SumArray Implementation 2

Constructor

```
SumArrayImpl2::SumArrayImpl2(int n) {
    numElements = n;
    array = new int[n];
    theSum = 0;  // Initialize sum to 0

    for(int i = 0; i < n; i++)
        array[i] = 0;
}
```

Destructor

```
SumArrayImpl2::~SumArrayImpl2() {
    delete [] array;
}
```

Get Function

```
int SumArrayImpl2::get(int index) {
    return array[index];
}
```

Set Function

```
void SumArrayImpl2::set(int index, int value) {
    theSum -= array[index];  // Subtract old value
    array[index] = value;    // Update array
    theSum += value;         // Add new value
}
```

Change:

1. Remove old value from sum
2. Update the array
3. Add new value to sum

SumArray Implementation 2

```
int SumArrayImpl2::sum() {
    return theSum;  // Just return the stored value!
}
```

This is the payoff:

- No loop needed
- No calculation needed
- Just return the pre-calculated sum
- **Time complexity: O(1)**

Performance Comparison

Implementation 1

Operation	Complexity
`get()`	O(1)
`set()`	O(1)
`sum()`	**O(n)**

Memory: O(n)

Strategy: Calculate when needed

Best when:

- Infrequent sum() calls
- Many set() operations

Implementation 2

Operation	Complexity
`get()`	O(1)
`set()`	O(1)
`sum()`	**O(1)**

Memory: O(n) + O(1)

Strategy: Maintain running total

Best when:

- Frequent sum() calls
- Trade memory for speed

Space-Time Tradeoff

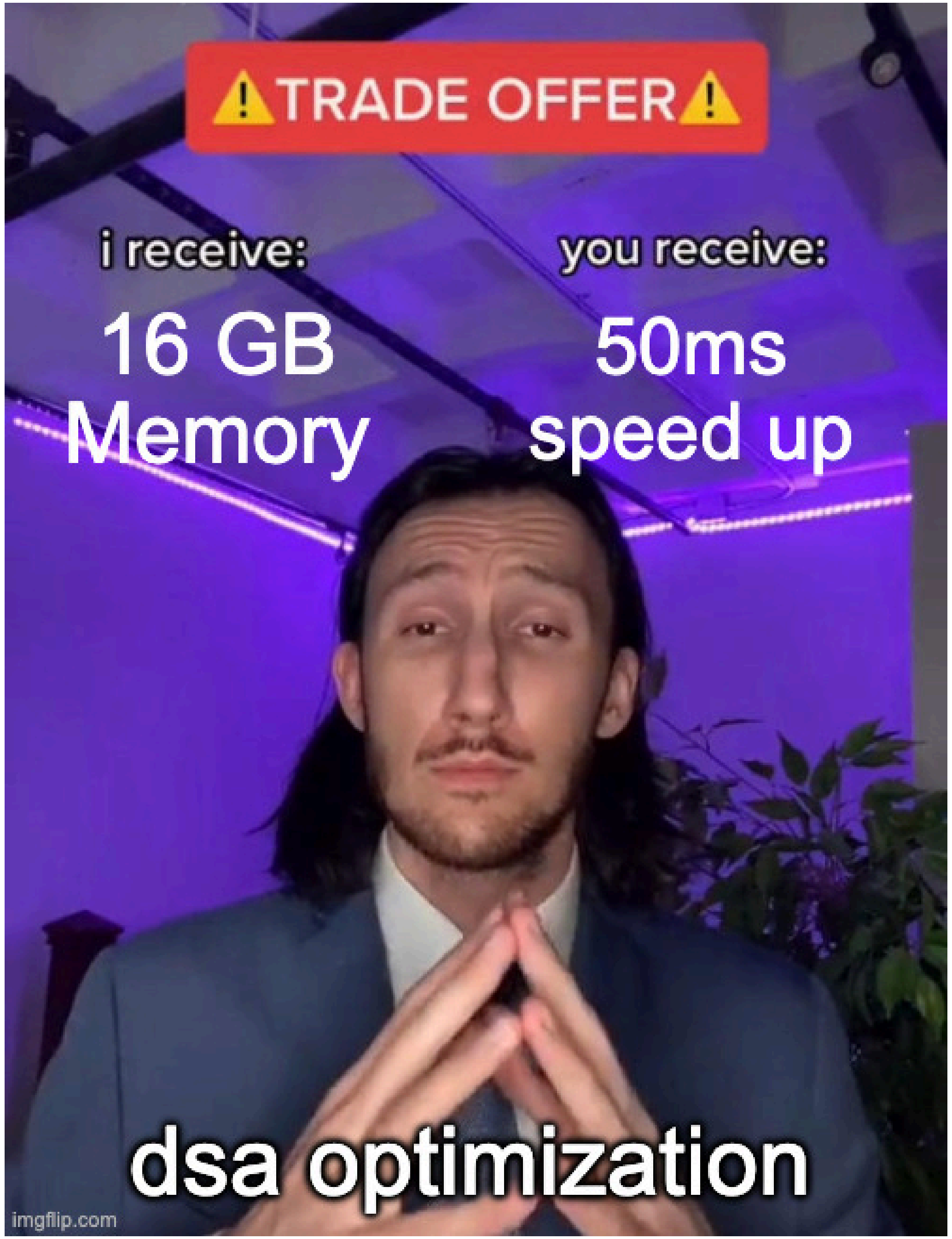
You often trade one resource for another:

- **Implementation 1**: Less memory, slower sum()
- **Implementation 2**: More memory, faster sum()

Like caching in web development:

- **No cache**: Compute every time (slow, less memory)
- **With cache**: Store results (fast, more memory)

There's no free lunch! Every optimization has a cost.



Why ADTs Matter

The ADT (What)

Car Interface:, Accelerate (press gas pedal), brake (press brake pedal), turn (rotate steering wheel), shift gears (use gear stick)

You don't need to know HOW: Combustion engine works, Brakes apply friction, Steering mechanism turns wheels

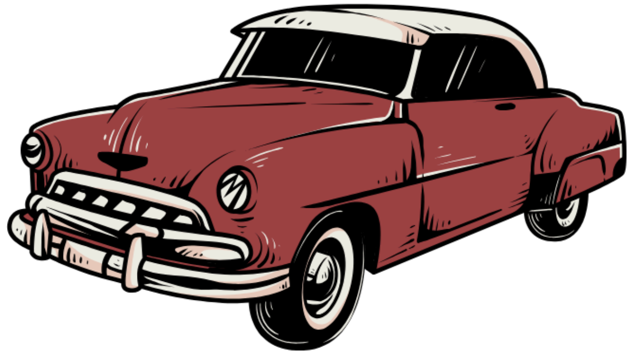
The Implementation (How)

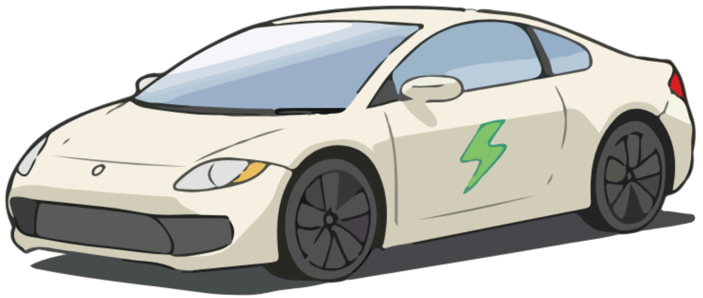
Different implementations:

- **Gas car**: Combustion engine
- **Electric car**: Electric motor
- **Hybrid car**: Both!

Same interface, different internals!

You can drive all three the same way, even though they work completely differently inside.





The ADT Advantage

Same Interface, Different Performance

```
SumArray* arr1 = new SumArrayImpl(1000);  // Calculate on demand
SumArray* arr2 = new SumArrayImpl2(1000);  // Maintain running sum

// Both work the same way to the user:
arr1->set(0, 100);
arr1->set(1, 200);
int s1 = arr1->sum();  // O(n) - slower

arr2->set(0, 100);
arr2->set(1, 200);
int s2 = arr2->sum();  // O(1) - faster!
```

Common Abstract Data Types

ADTs You'll Meet This Semester

ADT	Key Operations	Where are they?
List	add, remove, get, insert	Shopping list, todo list
Stack	push, pop, top	Stack of plates, undo history
Queue	enqueue, dequeue, front	Line at store, printer queue
Set	add, remove, contains	Mathematical set, unique items
Map	put, get, remove	Dictionary, phone book
Tree	insert, delete, search	Family tree, file system
Graph	addVertex, addEdge	Social network, road map

Each can be implemented in multiple ways!

ADT vs Data Structure

Abstract Data Type (ADT)

Conceptual/Logical view

- **What** operations exist
- **What** behavior to expect
- **Interface/Contract** Language-independent concept

Examples:

- List ADT
- Stack ADT
- Queue ADT

Think: ADT = Blueprint, Data Structure = Actual Building

Data Structure

Concrete/Physical view

- **How** it's implemented
- **How** data is organized
- **Actual code** Language-specific implementation

Examples:

- ArrayList (implements List)
- LinkedList (implements List)
- Array-based Stack
- Linked Stack

Benefits of ADTs

1. Separation of Concerns

User perspective: "I just want to store and retrieve data"
Implementation perspective: "I need to optimize memory and speed"

2. Flexibility

Change implementation without breaking user code:

```
ListADT* myList = new ArrayList();    // Using array
// ... later, switch to ...
ListADT* myList = new LinkedList();   // Using linked list
// Same interface, different performance!
```

3. Easier to Understand

Focus on **what** you're doing, not **how** it works internally.

Now, Let's Apply This to Lists

The List ADT

A **list** is a sequence of elements where:

- Elements are ordered (have positions: 0, 1, 2, ...)
- Duplicate elements are allowed
- Elements can be accessed by position

Common List Operations

- **Access**: Get element at position i
- **Insert**: Add element at position i
- **Delete**: Remove element at position i
- **Search**: Find element with value x
- **Size**: Get number of elements

Lists in Real Life

Digital World

- **Shopping cart** items
- **Todo list** tasks
- **Playlist** songs
- **Browser history**
- **Email inbox**
- **Social media feed**

Physical World

- **Queue** at a store
- **Deck of cards**
- **Books** on a shelf
- **Train cars** linked together
- **Chain links**

> The list is one of the most fundamental data structures in computer science.

Two Main Implementations

1. Array-Based List

```
class ArrayList {
private:
    int* data;
    int size;
    int capacity;
};
```

Characteristics:

- Contiguous memory
- Fast random access
- Fixed initial capacity
- May need resizing

2. Linked List

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

class LinkedList {
private:
    Node* head;
    int size;
};
```

Characteristics:

- Non-contiguous memory
- Dynamic size
- Sequential access
- No resizing needed

Array-Based Lists

Using Arrays to Store Lists

```
class ArrayList {
private:
    int* data;          // Dynamic array
    int size;           // Current number of elements
    int capacity;       // Current array capacity - useful to prevent memory overflow

public:
    ArrayList(int cap = 10);
    ~ArrayList();
    void add(int value);
    void insert(int index, int value);
    void remove(int index);
    int get(int index);
    int length() { return size; }
};
```

ArrayList Implementation: Constructor

```
class ArrayList {
private:
    int* data;
    int size;
    int capacity;

public:
    ArrayList(int cap = 10) {
        capacity = cap;
        size = 0;
        data = new int[capacity];  // Allocate array on heap
    }

    ~ArrayList() {
        delete[] data;  // Free memory
    }
};
```

Key Points:

- Initial capacity prevents frequent resizing
- Size tracks actual number of elements
- Destructor prevents memory leaks

ArrayList: Adding Elements

```
void add(int value) {
    if (size >= capacity) {
        resize();  // Need more space
    }
    data[size] = value;
    size++;
}

void resize() {
    capacity *= 2;  // Double the capacity
    int* newData = new int[capacity];

    // Copy old elements
    for (int i = 0; i < size; i++) {
        newData[i] = data[i];
    }

    delete[] data;  // Free old array
    data = newData;  // Point to new array
}
```

Time Complexity: O(1) amortized (occasional O(n) for resize)

ArrayList: Insertion at Position

```cpp
void insert(int index, int value) {
    if (index < 0 || index > size) {
        throw out_of_range("Invalid index");
    }

    if (size >= capacity) {
        resize();
    }

    // Shift elements to the right
    for (int i = size; i > index; i--) {
        data[i] = data[i - 1];
    }

    data[index] = value;
    size++;
}
```

Time Complexity: O(n) - Must shift elements

ArrayList Example

Inserting at Position 2

```
Initial array (size=5, capacity=8):
Index:  0   1   2   3   4   5   6   7
Data: [10][20][30][40][50][ ][ ][ ]

Insert 25 at index 2:

Step 1 - Shift elements right:
Index:  0   1   2   3   4   5   6   7
Data: [10][20][30][30][40][50][ ][ ]
                   ↑
Step 2 - Insert new value:
Index:  0   1   2   3   4   5   6   7
Data: [10][20][25][30][40][50][ ][ ]
              ↑ new
```

Result: size becomes 6

ArrayList: Deletion

```cpp
void remove(int index) {
    if (index < 0 || index >= size) {
        throw out_of_range("Invalid index");
    }

    // Shift elements to the left
    for (int i = index; i < size - 1; i++) {
        data[i] = data[i + 1];
    }

    size--;
}

int get(int index) {
    if (index < 0 || index >= size) {
        throw out_of_range("Invalid index");
    }
    return data[index];
}
```

Time Complexity:

- Remove: O(n) - Must shift elements
- Get: O(1) - Direct access

ArrayList: Performance Analysis

Time Complexity

Operation	Average Case	Worst Case
Access (get)	O(1)	O(1)
Add (end)	O(1)	O(n) (resize)
Insert	O(n)	O(n)
Remove	O(n)	O(n)
Search	O(n)	O(n)

Space Complexity

- **Storage:** O(n)
- **Overhead:** Wasted space when size < capacity

Linked Lists: Introduction

What is a Linked List?

A **linked list** is a linear data structure where:

- Elements are stored in **nodes**
- Each node contains **data** and a **pointer** to the next node
- Nodes are not stored contiguously in memory
- First node is called the **head**

```
struct Node {
    int data;       // The value
    Node* next;     // Pointer to next node

    Node(int val) : data(val), next(nullptr) {}
};
```

Linked List

Singly Linked List Structure

```
head
  ↓
┌────┬────┐     ┌────┬────┐     ┌────┬────┐     ┌────┬────┐
│ 10 │ ●──┼────→│ 20 │ ●──┼────→│ 30 │ ●──┼────→│ 40 │ ///│
└────┴────┘     └────┴────┘     └────┴────┘     └────┴────┘
  Node 1          Node 2          Node 3          Node 4
```

Key Points:

- Each node points to the next node
- Last node's `next` is `nullptr` (end of list)
- Head pointer gives access to the entire list

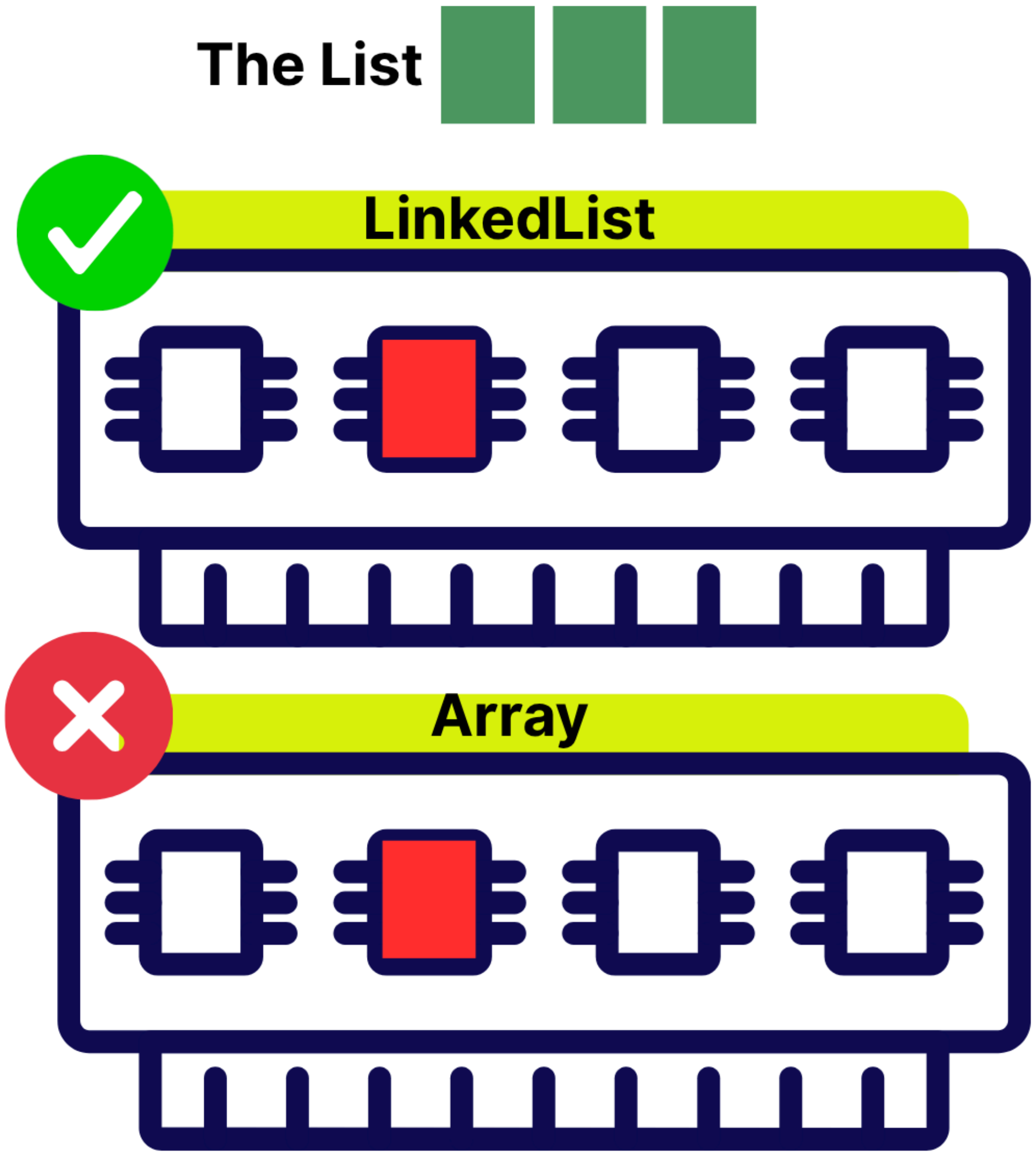
Linked List vs Array

Array

- ✅ Fast random access: `O(1)`
- ✅ Cache-friendly (contiguous)
- ❌ Fixed size (or expensive resize)
- ❌ Expensive insertions/deletions: `O(n)`
- ❌ All elements must be in the same type

LinkedList

- ❌ Slow random access: `O(n)`
- ❌ Not cache-friendly (scattered)
- ✅ Dynamic size
- ✅ Fast insertions/deletions: `O(1)`
- ✅ Elements can be in different types



The List
LinkedList
Array

Singly Linked List: Class Structure

```cpp
class LinkedList {
private:
    struct Node {
        int data;
        Node* next;

        Node(int val) : data(val), next(nullptr) {}
    };

    Node* head;
    int size;

public:
    LinkedList() : head(nullptr), size(0) {}
    ~LinkedList();

    void insertFront(int value);
    void insertBack(int value);
    void insertAt(int index, int value);
    void remove(int value);
    void display();
    int length() { return size; }
};
```

Linked List: Insert at Front

```cpp
void insertFront(int value) {
    Node* newNode = new Node(value);
    newNode->next = head;
    head = newNode;
    size++;
}
```

Example

```
Before: head → [20] → [30] → nullptr
Insert 10 at front:
        head
         ↓
       [10] ——→ [20] → [30] → nullptr
         ↑
     newNode
```

Time Complexity: O(1) - Constant time!

Linked List: Insert at Back

```
void insertBack(int value) {
    Node* newNode = new Node(value);

    if (head == nullptr) {
        head = newNode;
    } else {
        Node* current = head;
        // Traverse to the last node
        while (current->next != nullptr) {
            current = current->next;
        }
        current->next = newNode;
    }
    size++;
}
```

Time Complexity: O(n) - Must traverse entire list

Can we do better? 🙋

Linked List: Insert at Back - Optimized

Solution: Keep a `tail` pointer → O(1)

```cpp
class LinkedList {
private:
    Node* head;
    Node* tail;  // Add tail pointer!
    int size;

public:
    LinkedList() : head(nullptr), tail(nullptr), size(0) {}
};
```

With tail pointer, insertion at back becomes O(1)!

Linked List: Insert at Back - Optimized

```
void insertBack(int value) {
    Node* newNode = new Node(value);

    if (head == nullptr) {
        // Empty list: both head and tail point to new node
        head = tail = newNode;
    } else {
        // Add to end: update tail's next, then move tail
        tail->next = newNode;
        tail = newNode;
    }
    size++;
}
```

Time Complexity: O(1) - Direct access via tail pointer!

Trade-off: Extra memory for tail pointer

Linked List: Insert at Position

```
void insertAt(int index, int value) {
    if (index < 0 || index > size) {
        throw out_of_range("Invalid index");
    }

    if (index == 0) {
        insertFront(value);
        return;
    }

    Node* newNode = new Node(value);
    Node* current = head;

    // Traverse to node before insertion point
    for (int i = 0; i < index - 1; i++) {
        current = current->next;
    }

    newNode->next = current->next;
    current->next = newNode;
    size++;
}
```

Time Complexity: O(n) - Need to traverse to position

Insert at Position : Example

Insert 25 at index 2

```
Step 1: Traverse to index 1
head → [10] → [20] → [30] → nullptr
                ↑
             current

Step 2: Create new node
       [25]
     newNode

Step 3: Link new node
head → [10] → [20] → [30] → nullptr
                ↓      ↑
              [25] ───┘

Step 4: Relink previous node
head → [10] → [20] → [25] → [30] → nullptr
```

Linked List: Deletion

```
void remove(int value) {
    if (head == nullptr) return;

    // Special case: delete head
    if (head->data == value) {
        Node* temp = head;
        head = head->next;
        delete temp;
        size--;
        return;
    }

    // Find node before the one to delete
    Node* current = head;
    while (current->next != nullptr && current->next->data != value) {
        current = current->next;
    }

    if (current->next != nullptr) {
        Node* temp = current->next;
        current->next = current->next->next;
        delete temp;
        size--;
    }
}
```

Linked List: Delete Tail

The Problem: Even with a tail pointer, we need the node BEFORE tail!

```
void deleteTail() {
    if (head == nullptr) return;  // Empty list

    if (head == tail) {  // Only one node
        delete head;
        head = tail = nullptr;
        size--;
        return;
    }

    // Must traverse to find second-to-last node
    Node* current = head;
    while (current->next != tail) {
        current = current->next;
    }

    delete tail;
    tail = current;
    tail->next = nullptr;
    size--;
}
```

Time Complexity: Still O(n) - Need to find previous node!

Why Delete Tail is O(n) in Singly Linked List

The Fundamental Problem

```
Before deletion:
head → [10] → [20] → [30] → [40] ← tail
                       ↑
                 Need this node!
```

We need to:

1. Find the node BEFORE tail
2. Set its `next` to `nullptr`
3. Update `tail` pointer to this node

Why we can't do better:

- Singly linked list = **one-way street**
- Can't go backwards from tail
- Must start from head and traverse

Solution for O(1) deletion: Use **doubly linked list**

Deletion: Visual Example

Delete value 20

```
Initial:
head → [10] → [20] → [30] → nullptr

Step 1: Find node before target
head → [10] → [20] → [30] → nullptr
        ↑       ↑
     current  temp

Step 2: Relink and delete
head → [10] ──────→ [30] → nullptr

       [20]  ← delete this
       temp
```

Time Complexity: O(n) - Must search for value

Linked List: Traversal and Display

```
void display() {
    Node* current = head;

    while (current != nullptr) {
        cout << current->data;
        if (current->next != nullptr) {
            cout << " → ";
        }
        current = current->next;
    }
    cout << " → nullptr" << endl;
}

// Count nodes (alternative to size variable)
int count() {
    int cnt = 0;
    Node* current = head;

    while (current != nullptr) {
        cnt++;
        current = current->next;
    }
    return cnt;
}
```

Linked List: Destructor

```
~LinkedList() {
    Node* current = head;

    while (current != nullptr) {
        Node* next = current->next;  // Save next pointer
        delete current;              // Delete current node
        current = next;              // Move to next
    }

    head = nullptr;
    size = 0;
}
```

Critical: Must delete all nodes to prevent memory leaks!

Pattern: Save `next` before deleting, or you lose access to rest of list

Singly Linked List: Performance

Time Complexity

Operation	Complexity	Notes
Insert at head	O(1)	Direct pointer manipulation
Insert at tail	O(n)	Must traverse (O(1) with tail pointer)
Insert at position	O(n)	Must traverse to position
Delete	O(n)	Must search for value
Access by index	O(n)	Must traverse
Search	O(n)	Must traverse

Space Complexity

- **Per node:** 8 bytes (data) + 8 bytes (pointer) = 16 bytes
- **Overhead:** Higher than arrays due to pointers

Doubly Linked List

What's Different?

Each node has **two pointers:**

- `next` : Points to next node
- `prev` : Points to previous node

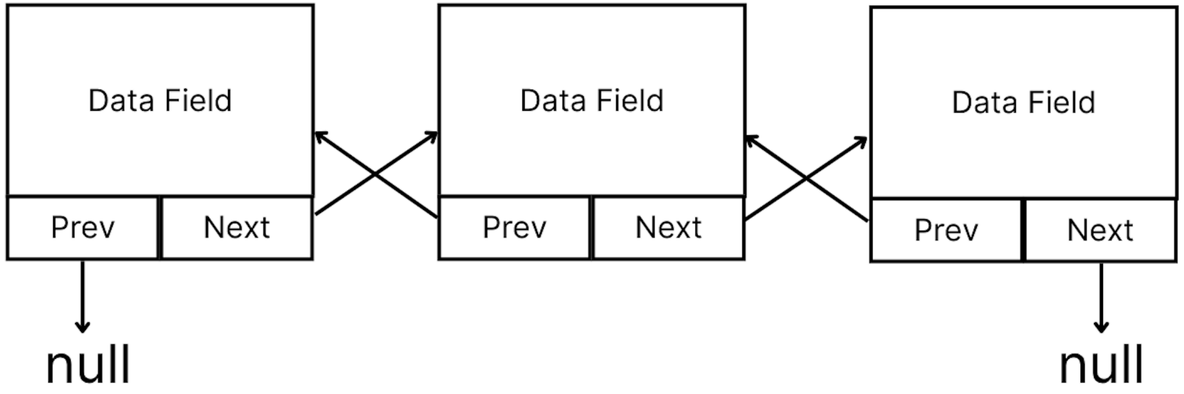
```
struct Node {
    int data;
    Node* next;
    Node* prev;  // New: pointer to previous node

    Node(int val) : data(val), next(nullptr), prev(nullptr) {}
};
```

Advantages:

- Can traverse in **both directions**
- Easier deletion (don't need previous node)
- More flexible operations

Doubly Linked List: Structure



Key Points:

- First node's `prev` is `nullptr`
- Last node's `next` is `nullptr`

Doubly Linked List: Class Structure

```
class DoublyLinkedList {
private:
    struct Node {
        int data;
        Node* next;
        Node* prev;

        Node(int val) : data(val), next(nullptr), prev(nullptr) {}
    };

    Node* head;
    Node* tail;  // Optional but useful
    int size;

public:
    DoublyLinkedList() : head(nullptr), tail(nullptr), size(0) {}
    ~DoublyLinkedList();

    void insertFront(int value);
    void insertBack(int value);
    void remove(Node* node);  // Can remove by node reference
    void displayForward();
    void displayBackward();
};
```

Doubly Linked List: Insert at Front

```
void insertFront(int value) {
    Node* newNode = new Node(value);

    if (head == nullptr) {
        // Empty list
        head = tail = newNode;
    } else {
        newNode->next = head;
        head->prev = newNode;
        head = newNode;
    }
    size++;
}
```

```
Before: head → [20] ⇄ [30] ← tail

After:  head → [10] ⇄ [20] ⇄ [30] ← tail
```

Doubly Linked List: Insert at Back

```
void insertBack(int value) {
    Node* newNode = new Node(value);

    if (tail == nullptr) {
        // Empty list
        head = tail = newNode;
    } else {
        tail->next = newNode;
        newNode->prev = tail;
        tail = newNode;
    }
    size++;
}
```

Time Complexity: O(1) - Because we have a tail pointer

Advantage over Singly Linked List: No need to traverse to find the end

What if No Tail Pointer?

Insert at Back Without Tail

Singly Linked List

```
// Must traverse
Node* current = head;
while (current->next != nullptr) {
    current = current->next;
}
current->next = newNode;
```

Time: O(n)

Doubly Linked List

```
// Still must traverse
Node* current = head;
while (current->next != nullptr) {
    current = current->next;
}
current->next = newNode;
newNode->prev = current;
```

Time: O(n)

Without tail pointer: No advantage for insertion at back! Both are O(n).

Doubly Linked List: Deletion

```cpp
void remove(Node* node) {
    if (node == nullptr) return;

    // Update previous node's next pointer
    if (node->prev != nullptr) {
        node->prev->next = node->next;
    } else {
        head = node->next;  // Deleting head
    }

    // Update next node's prev pointer
    if (node->next != nullptr) {
        node->next->prev = node->prev;
    } else {
        tail = node->prev;  // Deleting tail
    }

    delete node;
    size--;
}
```

Time Complexity: O(1) - If we have the node reference!

Doubly Linked List: Bidirectional Traversal

```
void displayForward() {
    Node* current = head;
    cout << "Forward: ";
    while (current != nullptr) {
        cout << current->data;
        if (current->next != nullptr) {
            cout << " ⇄ ";
        }
        current = current->next;
    }
    cout << endl;
}

void displayBackward() {
    Node* current = tail;
    cout << "Backward: ";
    while (current != nullptr) {
        cout << current->data;
        if (current->prev != nullptr) {
            cout << " ⇄ ";
        }
        current = current->prev;
    }
    cout << endl;
}
```

Comparison: Singly vs Doubly Linked List

Singly Linked List

Advantages:

- ✅ Less memory (one pointer per node)
- ✅ Simpler implementation
- ✅ Sufficient for many use cases

Disadvantages:

- ❌ One-way traversal only
- ❌ Need previous node for deletion
- ❌ Cannot traverse backward

Use when: Forward-only traversal is sufficient

Doubly Linked List

Advantages:

- ✅ Bidirectional traversal
- ✅ Easier deletion (O(1) with node ref)
- ✅ More flexible operations

Disadvantages:

- ❌ More memory (two pointers per node)
- ❌ More complex implementation
- ❌ More pointer updates

Use when: Need backward traversal or frequent deletions

Circular Linked Lists

Singly Circular

```
       ┌───────────────────────────────┐
       ↓                               │
head → [10] → [20] → [30] → [40] ──────┘
```

Last node points back to first node (no `nullptr`)

Doubly Circular

- **Last node's `next`** points to **first node**
- **First node's `prev`** points to **last node**

Doubly Circular Lists

Real-World Applications

1. Music Player (with shuffle history)

- Navigate forward/backward through songs
- Loop back to start when reaching end
- Example: Spotify playlist on repeat

2. Browser Tab Management

- Cycle through tabs: Ctrl+Tab (forward), Ctrl+Shift+Tab (backward)
- Last tab wraps to first tab

3. Image Carousel

- Slideshow that loops infinitely
- Can navigate both directions

Array-Based List vs Linked List

Feature	Array-Based	Linked List
Memory	Contiguous	Scattered
Access by index	O(1)	O(n)
Insert at front	O(n)	O(1)
Insert at end	O(1)*	O(n) or O(1)**
Insert middle	O(n)	O(n)
Delete	O(n)	O(n) or O(1)***
Space overhead	Low	High (pointers)
Cache performance	Good	Poor
Dynamic size	Resize needed	Natural

**Amortized, **With tail pointer, ***With node reference*

When to Use Array-Based Lists

Choose Arrays When:

1. **Random access is common**
    - Need to access elements by index frequently
    - Example: Video frames, game board
2. **Size is predictable**
    - Know approximate size in advance
    - Example: Days of the week, fixed configuration
3. **Memory is limited**
    - Less overhead per element
    - Cache-friendly for iteration
4. **Mostly append operations**
    - Adding to end is fast (amortized O(1))
    - Example: Log files, append-only data

When to Use Linked Lists

Choose Linked Lists When:

1. **Frequent insertions/deletions at front**
    - O(1) operation
    - Example: Undo/redo stack, queue implementation
2. **Size is unknown or highly variable**
    - No need to preallocate or resize
    - Example: Dynamic user input, real-time data
3. **Don't need random access**
    - Sequential access is fine
    - Example: Processing pipeline, iterators
4. **Memory fragmentation is acceptable**
    - Can use scattered memory
    - Large contiguous blocks not available

Common Linked List Problems

1. Finding the Middle

```
Node* findMiddle(Node* head) {
    Node* slow = head;
    Node* fast = head;

    // Fast moves 2x speed of slow
    while (fast != nullptr && fast->next != nullptr) {
        slow = slow->next;
        fast = fast->next->next;
    }

    return slow;  // When fast reaches end, slow is at middle
}
```

Technique: Two pointers (slow and fast)

Time Complexity: O(n)

Common Linked List Problems

2. Detecting a Cycle

```
bool hasCycle(Node* head) {
    Node* slow = head;
    Node* fast = head;

    while (fast != nullptr && fast->next != nullptr) {
        slow = slow->next;
        fast = fast->next->next;

        if (slow == fast) {
            return true;  // Cycle detected!
        }
    }

    return false;  // No cycle
}
```

Technique: Floyd's Cycle Detection (Tortoise and Hare)

Time Complexity: O(n)

Common Linked List Problems

3. Reversing a Linked List

```cpp
Node* reverse(Node* head) {
    Node* prev = nullptr;
    Node* current = head;

    while (current != nullptr) {
        Node* next = current->next;  // Save next
        current->next = prev;        // Reverse link
        prev = current;              // Move prev forward
        current = next;              // Move current forward
    }

    return prev;  // New head
}
```

Visual: [1]→[2]→[3]→nullptr becomes nullptr←[1]←[2]←[3]

Time Complexity: O(n)

Common Linked List Problems

4. Merging Two Sorted Lists

```
Node* mergeSorted(Node* l1, Node* l2) {
    if (l1 == nullptr) return l2;
    if (l2 == nullptr) return l1;

    Node* result = nullptr;

    if (l1->data <= l2->data) {
        result = l1;
        result->next = mergeSorted(l1->next, l2);
    } else {
        result = l2;
        result->next = mergeSorted(l1, l2->next);
    }

    return result;
}
```

Technique: Recursion

Time Complexity: O(m + n)

Common Linked List Problems

5. Removing Duplicates (Sorted List)

```
void removeDuplicates(Node* head) {
    Node* current = head;

    while (current != nullptr && current->next != nullptr) {
        if (current->data == current->next->data) {
            Node* temp = current->next;
            current->next = current->next->next;
            delete temp;
        } else {
            current = current->next;
        }
    }
}
```

Example: [1]→[1]→[2]→[3]→[3] becomes [1]→[2]→[3]

Time Complexity: O(n)

Memory Considerations

Array-Based List Memory

```
// ArrayList with capacity 100, size 10
int* data = new int[100];  // Allocated: 400 bytes
// Used: 40 bytes (10 elements)
// Wasted: 360 bytes (90 unused slots)
```

Memory usage: `capacity × sizeof(element)`

Waste: Can be significant if capacity >> size

Linked List Memory

```
// 10 nodes in singly linked list
// Per node: 4 bytes (int) + 8 bytes (pointer) = 12 bytes
// Total: 10 × 12 = 120 bytes
```

Memory usage: `size × (sizeof(data) + sizeof(pointer))`

Overhead: Fixed per node (pointer space)

Cache Performance

Why Arrays are Faster

```
Array in memory (contiguous):
┌────┬────┬────┬────┬────┬────┐
│ 10 │ 20 │ 30 │ 40 │ 50 │ 60 │  ← CPU loads entire block to cache
└────┴────┴────┴────┴────┴────┘
  ↑
 Fast sequential access (cache hits)
```

Why Linked Lists are Slower

```
Linked List in memory (scattered):
0x1000: [10]→0x5000       ← Cache miss
0x5000: [20]→0x2000       ← Cache miss
0x2000: [30]→0x8000       ← Cache miss
  ↑
Slow sequential access (cache misses)
```

Modern CPU cache lines: 64 bytes

Impact: Arrays can be 10-100x faster for sequential access

STL List Containers

C++ Standard Template Library

std::vector (Array-based)

```
#include <vector>

vector<int> vec;
vec.push_back(10);
vec.push_back(20);
vec[0];  // Random access
vec.size();
vec.clear();
```

Use case: Default choice for lists

std::list (Doubly Linked)

```
#include <list>

list<int> lst;
lst.push_front(10);
lst.push_back(20);
lst.front();  // No random access
lst.size();
lst.clear();
```

Use case: Frequent front insertions

std::forward_list (Singly Linked)

```
#include <forward_list>
forward_list<int> fwd;
fwd.push_front(10);  // Only front operations
```

Iterator Pattern

Traversing with Iterators

```
#include <vector>
#include <list>

vector<int> vec = {1, 2, 3, 4, 5};
list<int> lst = {1, 2, 3, 4, 5};

// Same iteration syntax for both!
for (auto it = vec.begin(); it != vec.end(); ++it) {
    cout << *it << " ";
}

for (auto it = lst.begin(); it != lst.end(); ++it) {
    cout << *it << " ";
}

// Or use range-based for loop
for (int val : vec) {
    cout << val << " ";
}
```

Benefit: Uniform interface across data structures

A Common Interview Question 📝

Remove nth Node from End

Interview Question: nth from End

```cpp
Node* nthFromEnd(Node* head, int n) {
    Node* fast = head;
    Node* slow = head;

    // Move fast n steps ahead
    for (int i = 0; i < n; i++) {
        if (fast == nullptr) return nullptr;  // n > list length
        fast = fast->next;
    }

    // Move both until fast reaches end
    while (fast != nullptr) {
        slow = slow->next;
        fast = fast->next;
    }

    return slow;  // nth from end
}
```

Technique: Two pointers with gap of n

Time Complexity: O(n)

Summary: Key Takeaways

Lists are Fundamental

1. **Two main implementations**: Array-based and Linked
2. **Trade-offs**: Access speed vs insertion/deletion speed
3. **Array-based**: Fast access, slow modifications
4. **Linked lists**: Slow access, fast modifications
5. **Choose based on use case**: Access pattern matters!

Linked List Varieties

- **Singly linked**: Simple, one-way traversal
- **Doubly linked**: Bidirectional, more flexible
- **Circular**: No end, useful for round-robin

Online Visualizations

- **VisuAlgo**: https://visualgo.net/en/list
    - Interactive linked list animations

Next Week Preview

Week 3: Stack and Queue

Building on lists, we'll explore:

- **Stack**: LIFO (Last In, First Out)
  - Applications: Function calls, undo/redo, expression evaluation
- **Queue**: FIFO (First In, First Out)
  - Applications: Task scheduling, breadth-first search
- **Implementations:** Using arrays and linked lists
- **Variations:** Circular queue, deque, priority queue

Reading Assignment

- **Weiss Chapter 3.6-3.7**: Stack and Queue
- **Review:** Linked list implementations

Thank You!

Contact Information

- **Email:** ekrem.cetinkaya@yildiz.edu.tr
- **Office Hours:** Tuesday 14:00-16:00 - Room F-B21
- **Book a slot before coming to the office hours:** Booking Link
- **Course Repository:** GitHub Link

Next Class

- **Date:** 15.10.2025
- **Topic:** Stack and Queue
- **Reading:** Weiss Chapter 3.6-3.7