Introduction

So far: only data structure is array

- Two ways to use an array
  - Static fixed-size array: compile-time known size

    ```
    int a[100];
    ```

  - Dynamically allocated fixed-size array:

    ```
    int n;
    cin >> n;
    int* b = new int[n]; //b will be a pointer to the first element of the array
    ```

    - You can't during execution later on change the size of the array
- Another way to use an array: resizable array
  - Make it look like the array is as big as you need it to be
  - Done typically inside a class

    ```
    Object {
        pointer to some dynamically allocated array
        size = 3; how many elements you are actually using
        CAP = 5; indication of the capacity of the array
    }

    operation add {
        if size is less than CAP --> there is room
        once we put one more, failure...
    }
    ```

  - Resizable array
    - If there is room, put element in dynamic array
    - If there is no room, allocate a new array
      - Go through old array and store everything into new array, update pointer, update capacity
      - Delete old array
  - In the standard library: **vector**

- Common property for all array-like random structures: consecutive storing of elements
  - Advantage
    - Quick random access `a[3]`
      - Compiler knows: location of array `a` + type of element
        - e.g. if type is double --> 8 bytes, then compiler just does `1000 + 8*k` for `a[k]`
      - trivial calculation
  - Disadvantage
    - Costly insertion/removal for ordered elements
      - Exception: insertion/removal at the end
        - delete/add one, change size -> cheap operation
        - do this when your items do not have to be ordered
      - If you want to add a new item between consecutive elements -> shift all elements to make room for insertion/removal
      - Insertion/removal near the beginning much more costly than end

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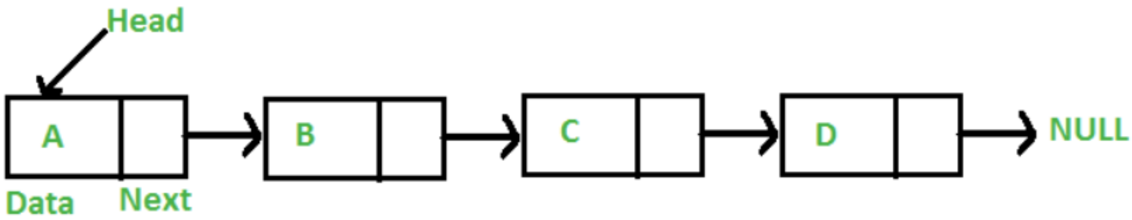
Linked List

> Goal: represent a collection of values for which inserting and removing items preserves the order of the other items, but is efficient even if the insertions are not at the end

- What if we don't require elements be stored one right after the other? (as in an array)
- Linked List General Idea
  - We can store each item in random addresses, we only follow the arrows
  - We have each item store its own value + a pointer to the next item
  - To insert: change the pointer of the previous item to point to new item, have new item's pointer point to next item
  - To remove: delete item's pointer, have previous item's pointer point to next item
  - To print: visit each item through the previous item, stop until we reach the `nullptr`
    - Our last item should point to the `nullptr` successor
    - To know our first item, we need a pointer variable `head` that points to the first item of the list
  - A list with no items: `head` points to the `nullptr`



> When working with linked lists, draw pictures!!

Using a Linked List Code

- Declaration of `Node`

```
struct Node
{
    int value; //value associated with the node
    Node* next; //pointer to the next node
};

Node* head; //pointer to the first node
```

  - `Node* next`: this is legal because compiler knows Node once it gotpass first line, and it knows the size of a pointer that is enoughinformation
  - `Node next`: this is ILLEGAL
    - how big is a node? size of Node = size of Node + size of int -->infinite
- Print the list in "order"
  - Idea 1 : while our head is not the nullptr, we print out the head'svalue and advance the head to the next

```
while (head != nullptr)
{
    cout << head-> value << endl;
    head = head -> next;
}
```

    - Code trace: we keep keep keep moving head until head is advanced tothe nullptr, everything is printed
      - head now points to a `nullptr`
      - PROBLEM: **memory leak**, lost access to the linked listbecause `head` is not pointing to the "first" node anymore, it ispointing to a null pointer

            - if we can't get to the first node, we can't get to *any*node

    - **Idea 2**: We don't change the `head` pointer, we use another pointervariable that is initialized to the `head` pointer

    ```
    for (Node* p = head; p != nullptr; p = p->next)
    {
        cout << p->value << endl;
    }
    ```

        - Code trace: we keep keep keep moving `p` until it points to the`nullptr`, leaves loop, local variable destroyed

            - Works for this case AND for a list with 1 item

        - Note: in the for loop, do not write `p++`!!

            - the `++` operators on pointers are only well defined if thepointer is pointing into an array

            - this is undefined behavior

            - likely, if a node is x bytes, advance `p` by x bytes --> youdon't know what is stored in this here --> some garbage value orrandom memory locations

        - Note: whenever you write `p-> ...`, makesure:

            - `p` is not uninitialized
            - `p` is not a `nullptr`

- Element Accessing (find the first occurrence of a value)

    - Idea 1: find the first occurence of 18 in the list, then exit loop

    ```
    Node* p;
    for (p = head; p->value!=18; p=p->next)
    {
        ; //empty statement, do nothing
    }
    ```

        - Problem:

            - "find *the* first node that is 18" implies existence, there isa node with 18

                - what about the possibility that the list does not contain18?

            - can I be sure `p` is uninitialized and not null?

                - for the empty list: `head` is pointing to nullptr, `p` isreaching for a null pointer

- end of list: null pointer as well, if `p`'s previous valueis pointing to the last node, then we will get the nullptr,and try to follow the null pointer
- we are going to have a problem if the list does not have an18

- Idea 2: Make sure that p is not the null pointer

```
for (p = head; p->value != 18 && p!=nullptr; p=p->next)
```

  - if `p` is a `nullptr`, this will be false -> get out of loop with`p` pointing to the null pointer
  - if before we get to the `p!=nullptr` statement, `p` is already anullptr and we follow a nullptr when checking `p->value != 18` -->that's undefined behavior

- **Idea 3**: Check for `p` being a nullptr **first**

```
for (p = head; p != nullptr && p->value !=18; p = p->next)
{
    ;
}
```

- Insertion (after a specified value)
  - **Idea 1**: Insert a node of value 54 after the 18 in the list, ifpresent
    - Check if only `p` is not a nullptr (if nullptr, then 18 is notpresent), now we know that `p` is a pointer to the `18` node
    - Somewhere in memory create a new node
    - Put it in value 54
    - Set 54 pointer to point to 42 (original node that 18 points to)
    - Change 18 node pointer to point to 54

```
if (p != nullptr)
{
    Node* newGuy = new Node; //dynamically allocate a new node
objectsomewhere in memory, newGuy will be pointer variable pointing
tothis node
    newGuy->value = 54; //set value
    newGuy->next = p->next; //we first set newGuy's pointer value
    p->next = newGuy; //now we have pointer
}
```

    - if we do:

```
p->next = newGuy;
newGuy->next = p->next;
```

We would effectively be setting newGuy's next pointer to point toitself -> infinite, and memory leak for the rest of the list

- when we leave the curly braces:
  - the local variable `newGuy` is destroyed
  - we do not need to `delete` anything manually because thedynamically allocated node is what we inserted, the pointer justgets deleted automatically

-note: the **right order**

- Insertion at the end (node 18 is the last node)
  - Works the same!

```
if (p != nullptr)
{
    Node* newGuy = new Node;
    newGuy->value = 54; //set value
    newGuy->next = p->next; //newGuy's pointer for nullptr
    p->next = newGuy; //now we have pointer
}
```

- Remove a node after a node (get rid of the node after the 18 node)
  - We can't do:
    - First set `p`'s next to 42 (`p->next->next`)
    - We now lost access to the 54 node, can't delete it
  - We also can't do:
    - First delete the 54 node (`p->next`)
    - We now lost access to the 42 node, can't make 18 node point to it
  - Idea 1:
    - Save 54 node pointer into some local variable, so we have avariable pointing to 42, delete 54 node, store local variable into 18
  - **Idea 2**:
    - Save a pointer to the 54 node
    - Change `p`'s next to point to the 42
    - delete the 54 node

```
Node* toBeDeleted = p->next; //hang on to the 54 node
p->next = toBeDeleted->next; //or p->next->next is fine too
delete toBeDeleted;
```

- Remove the node itself (remove node 18)
  - We can't follow a pointer backward in a singly-linked list
  - Method 1: Find the node before the 18
    - Idea:
      - The node before 18 points to the same node that `p` points to(`p` is the node we found)
      - Write another loop that starts from the beginning to check isyour next pointer the same value
      - Once we found this node, we delete node 18
  - Method 2: Two pointer variables
    - Idea:
      - `p` and another pointer variable that is following it
      - whenever you are ready to advance `p`, you store `p`'s valueinto the variable following `p`, then advance `p`, repeat
        - one pointer follows the other
      - once `p` is in the right place, the pointer following it is theone before
- Remove the node itself at the front of the list (Special Case)
  - We can't find a node before the first node, there is no node before it

```
//check if first node
head = p->next;
delete p;
```

Linked List Class Implementation

```
struct Node
{
    string value;
    Node *next;
}
```

The only member variable we need is a head pointer

```
class LinkedList
{
    public:
        LinkedList();
        void addToFront(string v);
        void addToRear(string v);
        void deleteItem(string v);
        bool findItem(string v);
        void printItems();
        ~LinkedList();
    private:
        Node *head;
};
```

Constructor: create an empty list (head pointer to nullptr)

```
LinkedList()
{
    head = nullptr;
}
```

Print Items in a List: loop through each of the nodes and print out values, starting with node pointed to by `head`

Linked List Traversal

```
void printItems()
{
    //Use a node pointer
    Node *p;
    p = head; //p points to 1st node

    while (p != nullptr)
    {
        cout << p->value << endl;
        p = p->next;
    }
}
```

Add an Item to a List

Add at top

```
void addToFront(string v)
{
    //allocate new node
    Node *p;
    p = new Node;

    p->value = v; //set value

    //Link new node to current top node
    p->next = head;

    //Update head pointer to new top node
    head = p;
}
```

Add at rear

- Two cases:
  - Empty list: same as adding new node to front
  - Non-empty list: traverse down links until we find the current last node
    - Use a `temp` variable to traverse to current last node
    - Allocate a new node, set value in node
    - Link the current last node to new node
    - Link last node to nullptr

```
void addToRear(string v)
{
    if (head == nullptr)
    {
        addToFront(v);
    }
    else
    {
        Node *p;
        p = head; //start at top node
        while (p->next != nullptr)
        {
            p = p->next;
        }
        Node *n = new Node;
        n->value = v;
        p->next = n;
        n->next = nullptr;
    }
}
```

Add Anywhere

- Several Cases:
  - If empty list: `addToFront()`
  - If new node belongs at top of list (sorted etc.): `addToFront()`
  - If new node belongs in middle of list
    - Use a traversal loop to find the node just ABOVE where you want to insert your new item
    - Allocate and fill new node
    - Link new node into list right after the ABOVE node

```
void AddItem(string newItem)
{
    if (head == nullptr)
    {
        AddToFront(newItem);
    }
    else if (/*decide if new item belongs at the top*/)
    {
        AddToFront(newItem);
    }
    else //new node belongs somewhere in the middle
    {
        Node *p = head;
        while (p->next != nullptr)
        {
            if (/*p points just above where to insert*/)
            {
                break;
            }
            p = p->next;
        }
        Node *latest = new Node;
        latest->value = newItem;
        latest->next = p->next;
        p->next = latest;
    }
}
```

Delete Item from the List

- Two cases:
  - Check if list is empty first -> if then return
  - Deleting the first node

        - If value is value of first node
        - Set node to delete = address of top node
        - Update head to point to the second node in list
        - Delete target node
        - Return
    - Deleting interior or last node
        - Traverse down the list until find node ABOVE the one to delete (so we can relink)
            - If p->next is not a nulltpr and is p->next->value is the value we want
        - If found target node
            - killMe = addr of target node
            - Link node above the node below
            - Delete target node

```
void deleteItem(string v)
{
    if (head == nullptr) { return; }

    if (head->value == v)
    {
        Node *killMe = head;
        head = killMe->next;
        delete killMe;
        return
    }

    Node*p = head;
    while (p != nullptr)
    {
        if (p->next != nullptr && p->next->value == v)
        {
            break; //p points to node above
        }
        p = p->next;
    }
    if (p != nullptr) //found our value
    {
        Node *killMe = p->next;
        p->next = killMe->next;
        delete killMe;
    }
}
```

Linked List Destruction

- Traverse the list with temp variable `p`
- Before we delete the node pointed to buy p
  - Save the location of the next node in a temp variable

```
~LinkedList()
{
    Node *p;
    p = head;
    while (p != nullptr)
    {
        Node *n = p->next;
        delete p;
        p = n;
    }
}
```

Disadvantages of Linked Lists (Singly)

- Complex to implement compared to arrays
- Element accessing
  - To access the kth item, have to travese down k - 1 times from the head
- To add an item at the end -> traverse through all N existing nodes

Tail Pointers and Linked Lists

> A tail pointer is a pointer that always points to the last node of the list

- We can now add new items to the end of our list without traversing

```
class LinkedList
{
    public:
        LinkedList();
        void addToFront(string v);
        ...
    private:
        Node *head;
        Node *tail;
};
```

New `addToRear()` function

- No longer need traversal loop, tail pointer already points to last node

```
void addToRear(string v)
{
    if (head == nullptr)
    {
        addToFront(v);
    }
    else
    {
        Node *n = new Node;
        n->value = v;
        tail->next = n; //linked prev last node to curr
        n->next = nullptr;
        tail = n;
    }
}
```

Doubly-linked lists

A doubly-linked list has both `next` and `previous` pointers in every node

```
struct Node
{
    string value;
    Node* next;
    Node* prev;
};
```

- Everytime we insert a new node or delete an existing node -> update 3 sets of pointers
    - The new nodes's next and prev pointers
    - The previous node's next pointer
    - The following node's previous pointer

Linked List Cheat Sheet

Given a pointer to a node: `Node *ptr`

NEVER access a node's data until validating its pointer

```
if (ptr != nullptr)
{
    cout << ptr->value;
}
```

To advance `ptr` to the next node/end of the list

```
if (ptr != nullptr)
{
    ptr = ptr->next;
}
```

To see if `ptr` points to the last node in a list

```
if (ptr != nullptr && ptr->next == nullptr)
{
    //then ptr points to the last node
}
```

To get to the next node's data

```
if (ptr != nullptr && ptr->next != nullptr)
{
    cout << ptr->next->value;
}
```

To get the head node's data:

```
if (head != nullptr)
{
    cout << head->value;
}
```

To check is a list is empty

```
if (head == nullptr)
{
    cout << "List is empty";
}
```

To check if a pointer points to the first node in a list

```
if (ptr == head)
{
    cout << "ptr is the first node";
}
```

Linked Lists with a Dummy Node

> Replacing head pointer with a dummy node gets rid of special cases

- Steps:
    - Get rid of head pointer
    - Add a node member variable to class `dummy`
        - Hold no value
    - Update your member functions to use the dummy node
- Constructor
    - Set `dummy.next` to `nullptr`
    - Initialize node's value
- Delete Item Function
    - Find the node above the one you want to delete
    - Relink above ndoe to node below
    - Delete the target node
- Add to End Function
    - Loop to find the last node
    - Allocate a new node
    - Initialize the new node
    - Update last node's next pointer to point to new node
- Notes:
    - Draw pictures!
    - Don't do things in the wrong order
        - Advice: set values in a new nodes first (usually)
    - Whenever you write p->... make sure:
        - `p` has a well-deinfed value (i.e. it's not uninitialized)
        - `p` is not nullptr
    - Boundary conditions for Linked-lists
        - An algorithm that works does not work correctly at beginning/end of list--> test!

            - Trace through middle of the list, beginning, and end
            - Trace through empty list
            - Trace through a one-element list
                - the node itself is the front and back of the list
    - End of the list : the only way to get there is to traverse all the way to the end
        - if you find that you have alot of operations there-> lets maintain a second pointer `tail` pointing to the last node of the list
        - Add a new node
            - dynamically allocate a new node, add value, put nullptr
            - set original last node's `next` to the last node
            - set tail to point to the last node
            - Special case: list empty

            ```
             head   tail
            [null] [null]
            ```

                - create a new node
                - there IS NO PREVIOUS node
                - make `tail` point to the new node
                - make `head` point to the new node as well
- Doubly-linked list
    - Arrange for every node to have two pointers
        - `next` pointer
        - `previous` pointer: points to predecessor node
    - Now if we want to remove node 18:
        - 18's predecessor will point to 18's successor
        - 18's successor will point to 18's predecessor
        - delete node 18
    - Twice as many pointers