Linked Lists

15 minutes

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In the university setting, it's common for Linked Lists to appear early on in an undergraduate's Computer Science coursework. While they don't always have the most practical real-world applications in industry, Linked Lists make for an important and effective educational tool in helping develop a student's mental model on what data structures actually are to begin with.

Linked lists are simple. They have many compelling, reoccurring edge cases to consider that emphasize to the student the need for care and intent while implementing data structures. They can be applied as the underlying data structure while implementing a variety of other prevalent abstract data types, such as Lists, Stacks, and Queues, and they have a level of versatility high enough to clearly illustrate the value of the Object Oriented Programming paradigm.

They also come up in software engineering interviews quite often.

What is a Linked List?

A Linked List data structure represents a linear sequence of "vertices" (or "nodes"), and tracks three important properties.

Linked List Properties:

Property	Description
`head`	The first node in the list.
`tail`	The last node in the list.
`length`	The number of nodes in the list; the list's length.

The data being tracked by a particular Linked List does not live inside the Linked List instance itself. Instead, each vertex is actually an instance of an even simpler, smaller data structure, often referred to as a "Node".

Depending on the type of Linked List (there are many), Node instances track some very important properties as well.

Linked List Node Properties:

Property	Description
`value`	The actual value this node represents.
`next`	The next node in the list (relative to this node).

`previous`	The previous node in the list (relative to this node).

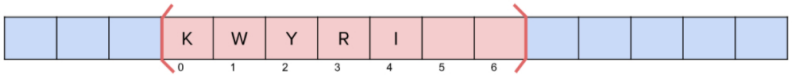
NOTE: The previous property is for Doubly Linked Lists only!

Linked Lists contain *ordered* data, just like arrays. The first node in the list is, indeed, first. From the perspective of the very first node in the list, the *next* node is the second node. From the perspective of the second node in the list, the *previous* node is the first node, and the *next* node is the third node. And so it goes.

"So...this sounds a lot like an Array..."

Admittedly, this does *sound* a lot like an Array so far, and that's because Arrays and Linked Lists are both implementations of the List ADT. However, there is an incredibly important distinction to be made between Arrays and Linked Lists, and that is how they *physically store* their data. (As opposed to how they *represent* the order of their data.)

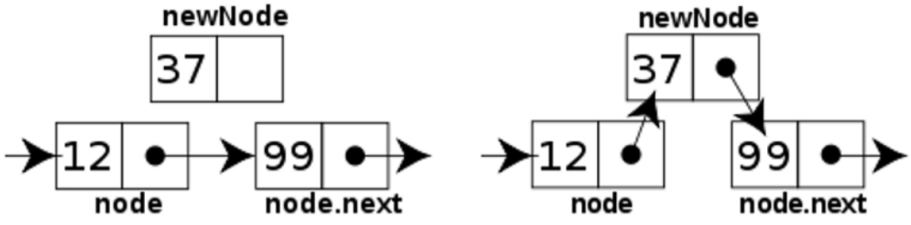
Recall that Arrays contain *contiguous* data. Each element of an array is actually stored *next to* it's neighboring element *in the actual hardware of your machine*, in a single continuous block in memory.



An Array's contiguous data being stored in a continuous block of addresses in memory.

Unlike Arrays, Linked Lists contain *non-contiguous* data. Though Linked Lists *represent* data that is ordered linearly, that mental model is just that - an interpretation of the *representation* of information, not reality.

In reality, in the actual hardware of your machine, whether it be in disk or in memory, a Linked List's Nodes are not stored in a single continuous block of addresses. Rather, Linked List Nodes live at randomly distributed addresses throughout your machine! The only reason we know which node comes next in the list is because we've assigned its reference to the current node's `next` pointer.



A Singly Linked List's non-contiguous data (Nodes) being stored at randomly distributed addresses in memory.

For this reason, Linked List Nodes have *no indices*, and no *random access*. Without random access, we do not have the ability to look up an individual Linked List Node in constant time. Instead, to find a particular Node, we have to start at the very first Node and iterate through the Linked List one node at a

time, checking each Node's *next* Node until we find the one we're interested in.

So when implementing a Linked List, we actually must implement both the Linked List class *and* the Node class. Since the actual data lives in the Nodes, it's simpler to implement the Node class first.

Types of Linked Lists

There are four flavors of Linked List you should be familiar with when walking into your job interviews.

Linked List Types:

List Type	Description	Directionality
Singly Linked	Nodes have a single pointer connecting them in a single direction.	Head→Tail
Doubly Linked	Nodes have two pointers connecting them bi-directionally.	Head⇄Tail
Multiply Linked	Nodes have two or more pointers, providing a variety of potential node orderings.	Head⇄Tail, A→Z, Jan→Dec, etc.
Circularly Linked	Final node's `next` pointer points to the first node, creating a non-linear, circular version of a Linked List.	Head→Tail→Head→Tail

NOTE: These Linked List types are not always mutually exclusive.

For instance:

- Any type of Linked List can be implemented Circularly (e.g. A Circular Doubly Linked List).
- A Doubly Linked List is actually just a special case of a Multiply Linked List.

You are most likely to encounter Singly and Doubly Linked Lists in your upcoming job search, so we are going to focus exclusively on those two moving forward. However, in more senior level interviews, it is very valuable to have some familiarity with the other types of Linked Lists. Though you may not actually code them out, *you will win extra points by illustrating your ability to weigh the tradeoffs of your technical decisions* by discussing how your choice of Linked List type may affect the efficiency of the solutions you propose.

Linked List Methods

Linked Lists are great foundation builders when learning about data structures because they share a number of similar methods (and edge cases) with many other common data structures. You will find that many of the concepts discussed here will repeat themselves as we dive into some of the more complex non-linear data structures later on, like Trees and Graphs.

In the project that follows, we will implement the following Linked List methods:

Type	Name	Description	Returns

Insertion	`addToTail`	Adds a new node to the tail of the Linked List.	Updated Linked List
Insertion	`addToHead`	Adds a new node to the head of the Linked List.	Updated Linked List
Insertion	`insertAt`	Inserts a new node at the "index", or position, specified.	Boolean
Deletion	`removeTail`	Removes the node at the tail of the Linked List.	Removed node
Deletion	`removeHead`	Removes the node at the head of the Linked List.	Removed node
Deletion	`removeFrom`	Removes the node at the "index", or position, specified.	Removed node
Search	`contains`	Searches the Linked List for a node with the value specified.	Boolean
Access	`get`	Gets the node at the "index", or position, specified.	Node at index
Access	`set`	Updates the value of a node at the "index", or position, specified.	Boolean
Meta	`size`	Returns the current size of the Linked List.	Integer

Time and Space Complexity Analysis

Before we begin our analysis, here is a quick summary of the Time and Space constraints of each Linked List Operation. The complexities below apply to both Singly and Doubly Linked Lists:

Data Structure Operation	Time Complexity (Avg)	Time Complexity (Worst)	Space Complexity (Worst)
Access	`Θ(n)`	`O(n)`	`O(n)`
Search	`Θ(n)`	`O(n)`	`O(n)`
Insertion	`Θ(1)`	`O(1)`	`O(n)`
Deletion	`Θ(1)`	`O(1)`	`O(n)`

Before moving forward, see if you can reason to yourself why each operation has the time and space complexity listed above!

Time Complexity - Access and Search:

Scenarios:

1. We have a Linked List, and we'd like to find the 8th item in the list.
2. We have a Linked List of sorted alphabet letters, and we'd like to see if the letter "Q" is inside that list.

Discussion:

Unlike Arrays, Linked Lists Nodes are not stored contiguously in memory, and thereby do not have an indexed set of memory addresses at which we can quickly lookup individual nodes in constant time. Instead, we must begin at the head of the list (or possibly at the tail, if we have a Doubly Linked List), and iterate through the list until we arrive at the node of interest.

In Scenario 1, we'll know we're there because we've iterated 8 times. In Scenario 2, we'll know we're there because, while iterating, we've checked each node's value and found one that matches our target value, "Q".

node's value and found one that matches our target value, `2`.

In the worst case scenario, we may have to traverse the entire Linked List until we arrive at the final node. This makes both Access & Search **Linear Time** operations.

Time Complexity - Insertion and Deletion:

Scenarios:

1. We have an empty Linked List, and we'd like to insert our first node.
2. We have a Linked List, and we'd like to insert or delete a node at the Head or Tail.
3. We have a Linked List, and we'd like to insert or delete a node from somewhere in the middle of the list.

Discussion:

Since we have our Linked List Nodes stored in a non-contiguous manner that relies on pointers to keep track of where the next and previous nodes live, Linked Lists liberate us from the linear time nature of Array insertions and deletions. We no longer have to adjust the position at which each node/element is stored after making an insertion at a particular position in the list. Instead, if we want to insert a new node at position `i`, we can simply:

1. Create a new node.
2. Set the new node's `next` and `previous` pointers to the nodes that live at positions `i` and `i - 1`, respectively.
3. Adjust the `next` pointer of the node that lives at position `i - 1` to point to the new node.
4. Adjust the `previous` pointer of the node that lives at position `i` to point to the new node.

And we're done, in Constant Time. No iterating across the entire list necessary.

"But hold on one second," you may be thinking. "In order to insert a new node in the middle of the list, don't we have to lookup its position? Doesn't that take linear time?!"

Yes, it is tempting to call insertion or deletion in the middle of a Linked List a linear time operation since there is lookup involved. However, it's usually the case that you'll already have a reference to the node where your desired insertion or deletion will occur.

For this reason, we separate the Access time complexity from the Insertion/Deletion time complexity, and formally state that Insertion and

Deletion in a Linked List are **Constant Time** across the board.

NOTE:

Without a reference to the node at which an insertion or deletion will occur, due to linear time lookup, an insertion or deletion *in the middle* of a Linked List will still take Linear Time, sum total.

Space Complexity:

Scenarios:

1. We're given a Linked List, and need to operate on it.
2. We've decided to create a new Linked List as part of strategy to solve some problem.

Discussion:

It's obvious that Linked Lists have one node for every one item in the list, and for that reason we know that Linked Lists take up Linear Space in memory. However, when asked in an interview setting what the Space Complexity *of your solution* to a problem is, it's important to recognize the difference between the two scenarios above.

In Scenario 1, we *are not* creating a new Linked List. We simply need to operate on the one given. Since we are not storing a *new* node for every node represented in the Linked List we are provided, our solution is *not necessarily* linear in space.

In Scenario 2, we *are* creating a new Linked List. If the number of nodes we create is linearly correlated to the size of our input data, we are now operating in Linear Space.

NOTE:

Linked Lists can be traversed both iteratively and recursively. *If you choose to traverse a Linked List recursively*, there will be a recursive function call added to the call stack for every node in the Linked List. Even if you're provided the Linked List, as in Scenario 1, you will still use Linear Space in the call stack, and that counts.

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