3.1 List abstract data type (ADT)

List abstract data type

A ***list*** is a common ADT for holding ordered data, having operations like append a data item, remove a data item, search whether a data item exists, and print the list. Ex: For a given list item, after "Append 7", "Append 9", and "Append 5", then "Print" will print (7, 9, 5) in that order, and "Search 8" would indicate item not found. A user need not have knowledge of the internal implementation of the list ADT. Examples in this section assume the data items are integers, but a list commonly holds other kinds of data like strings or entire objects.

PARTICIPATION ACTIVITY 3.1.1: List ADT.

Animation captions:

1. A new list named "ages" is created. Items can be appended to the list. The items are ordered.
2. Printing the list prints the items in order.
3. Removing an item keeps the remaining items in order.

PARTICIPATION ACTIVITY 3.1.2: List ADT.

Type the list after the given operations. Each question starts with an empty list. Type the list as: 5, 7, 9

1) Append(list, 3)
Append(list, 2)

Check Show answer

2) Append(list, 3)
Append(list, 2)
Append(list, 1)
Remove(list, 3)

Check Show answer

3) After the following operations, will Search(list, 2) find an item? Type yes or no.

Append(list, 3)
Append(list, 2)
Append(list, 1)
Remove(list, 2)

Check Show answer

Common list ADT operations

Table 3.1.1: Some common operations for a list ADT.

Operation	Description	Example starting with list: 99, 77
Append(list, x)	Inserts x at end of list	Append(list, 44), list: 99, 77, 44
Prepend(list, x)	Inserts x at start of list	Prepend(list, 44), list: 44, 99, 77
InsertAfter(list, w, x)	Inserts x after w	InsertAfter(list, 99, 44), list: 99, 44, 77
Remove(list, x)	Removes x	Remove(list, 77), list: 99
Search(list, x)	Returns item if found, else returns null	Search(list, 99), returns item 99 Search(list, 22), returns null
Print(list)	Prints list's items in order	Print(list) outputs: 99, 77
PrintReverse(list)	Prints list's items in reverse order	PrintReverse(list) outputs: 77, 99
Sort(list)	Sorts the lists items in ascending order	list becomes: 77, 99
IsEmpty(list)	Returns true if list has no items	For list 99, 77, IsEmpty(list) returns false
GetLength(list)	Returns the number of items in the list	GetLength(list) returns 2

PARTICIPATION ACTIVITY 3.1.3: List ADT common operations.

1) Given a list with items 40, 888, -3, 2, what does GetLength(list) return?
   - 4
   - Fails

2) Given a list with items 'Z', 'A', 'B', Sort(list) yields 'A', 'B', 'Z'.
   - True
   - False

3) If a list ADT has operations like Sort or PrintReverse, the list is clearly implemented using an array.
   - True
   - False

3.2 Singly-linked lists

Singly-linked list data structure

A ***singly-linked list*** is a data structure for implementing a list ADT, where each node has data and a pointer to the next node. The list structure typically has pointers to the list's first node and last node. A singly-linked list's first node is called the ***head***, and the last node the ***tail***. A singly-linked list is a type of ***positional list***: A list where elements contain pointers to the next and/or previous elements in the list.

null

null *is a special value indicating a pointer points to nothing.*

The name used to represent a pointer (or reference) that points to nothing varies between programming languages and includes nil, nullptr, None, NULL, and even the value 0.

PARTICIPATION ACTIVITY 3.2.1: Singly-linked list: Each node points to the next node.

Animation content:

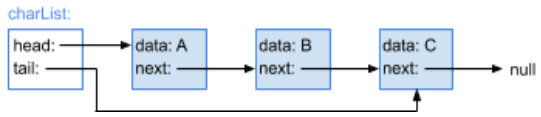
undefined

Animation captions:

1. A new list item is created, with the head and tail pointers pointing to nothing (null), meaning the list is empty.
2. ListAppend points the list's head and tail pointers to a new node, whose next pointer points to null.
3. Another append points the last node's next pointer and the list's tail pointer to the new node.
4. Operations like ListAppend, ListPrepend, ListInsertAfter, and ListRemove, update just a few relevant pointers.
5. The list's first node is called the head. The last node is the tail.

PARTICIPATION ACTIVITY 3.2.2: Singly-linked list data structure.

1) Given charList, C's next pointer value is _____.

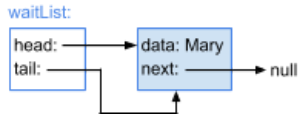


Check Show answer

2) Given attendList, the head node's data value is _____.
(Answer "None" if no head exists)

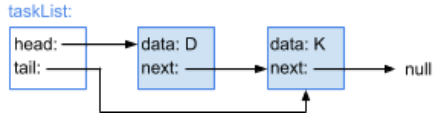
Check Show answer

3) Given waitList, the tail node's data value is _____.
(Answer "None" if no tail exists)



Check Show answer

4) Given taskList, node D is followed by node _____.



Check Show answer

Appending a node to a singly-linked list

Given a new node, the ***Append*** operation for a singly-linked list inserts the new node after the list's tail node. Ex: ListAppend(numsList, node 45) appends node 45 to numsList. The notation "node 45" represents a pointer to a newly created node or an existing node in a list with a data value of 45. This material does not discuss language-specific topics on object creation or memory allocation.

The append algorithm behavior differs if the list is empty versus not empty:

- *Append to empty list:* If the list's head pointer is null (empty), the algorithm points the list's head and tail pointers to the new node.
- *Append to non-empty list:* If the list's head pointer is not null (not empty), the algorithm points the tail node's next pointer and the list's tail pointer to the new node.

PARTICIPATION ACTIVITY 3.2.3: Singly-linked list: Appending a node.

Animation content:

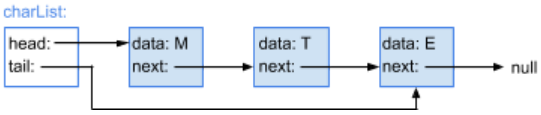
undefined

Animation captions:

1. Appending an item to an empty list updates both the list's head and tail pointers.
2. Appending to a non-empty list adds the new node after the tail node and updates the tail pointer.

PARTICIPATION ACTIVITY 3.2.4: Appending a node to a singly-linked list.

1) Appending node D to charList updates which node's next pointer?

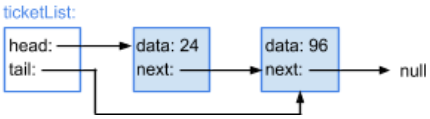


- M
- T
- E

2) Appending node W to sampleList updates which of sampleList's pointers?

- head and tail
- head only
- tail only

3) Which statement is NOT executed when node 70 is appended to ticketList?



- `list→head = newNode`
- `list→tail→next = newNode`
- `list→tail = newNode`

Prepending a node to a singly-linked list

Given a new node, the ***Prepend*** operation for a singly-linked list inserts the new node before the list's head node. The prepend algorithm behavior differs if the list is empty versus not empty:

- *Prepend to empty list:* If the list's head pointer is null (empty), the algorithm points the list's head and tail pointers to the new node.
- *Prepend to non-empty list:* If the list's head pointer is not null (not empty), the algorithm points the new node's next pointer to the head node, and then points the list's head pointer to the new node.

PARTICIPATION ACTIVITY 3.2.5: Singly-linked list: Prepending a node.

Animation content:

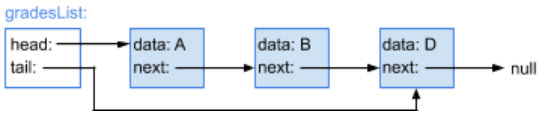
undefined

Animation captions:

1. Prepending an item to an empty list points the list's head and tail pointers to new node.
2. Prepending to a non-empty list points the new node's next pointer to the list's head node.
3. Prepending then points the list's head pointer to the new node.

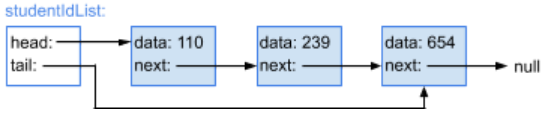
PARTICIPATION ACTIVITY 3.2.6: Prepending a node in a singly-linked list.

1) Prepending C to gradesList updates which pointer?



- The list's head pointer
- A's next pointer
- D's next pointer

2) Prepending node 789 to studentIdList updates the list's tail pointer.



- True
- False

3) Prepending node 6 to parkingList updates the list's tail pointer.

- True
- False

4) Prepending Evelyn to deliveryList executes which statement?

- `list→head = null`
- `newNode→next = list→head`
- `list→tail = newNode`

CHALLENGE ACTIVITY 3.2.1: Singly-linked lists.

Start

numList = new List
ListAppend(numList, node 46)
ListAppend(numList, node 82)
ListAppend(numList, node 59)
ListAppend(numList, node 96)

numList is now: Ex: 1, 2, 3

1 2 3 4 5

Check Next

3.3 Singly-linked lists: Insert

Given a new node, the ***InsertAfter*** operation for a singly-linked list inserts the new node after a provided existing list node. curNode is a pointer to an existing list node, but can be null when inserting into an empty list. The InsertAfter algorithm considers three insertion scenarios:

- *Insert as list's first node:* If the list's head pointer is null, the algorithm points the list's head and tail pointers to the new node.
- *Insert after list's tail node:* If the list's head pointer is not null (list not empty) and curNode points to the list's tail node, the algorithm points the tail node's next pointer and the list's tail pointer to the new node.
- *Insert in middle of list:* If the list's head pointer is not null (list not empty) and curNode does not point to the list's tail node, the algorithm points the new node's next pointer to curNode's next node, and then points curNode's next pointer to the new node.

PARTICIPATION ACTIVITY 3.3.1: Singly-linked list: Insert nodes.

Animation content:

undefined

Animation captions:

1. Inserting the list's first node points the list's head and tail pointers to newNode.
2. Inserting after the tail node points the tail node's next pointer to newNode.
3. Then, the list's tail pointer is pointed to newNode.
4. Inserting into the middle of the list points newNode's next pointer to curNode's next node.
5. Then, curNode's next pointer is pointed to newNode.

PARTICIPATION ACTIVITY 3.3.2: Inserting nodes in a singly-linked list.

Type the list after the given operations. Type the list as: 5, 7, 9

1) numsList: 5, 9

ListInsertAfter(numsList, node 9, node 4)

numsList:

Check Show answer

2) numsList: 23, 17, 8

ListInsertAfter(numsList, node 23, node 5)

numsList:

Check Show answer

3) numsList: 1

ListInsertAfter(numsList, node 1, node 6)
ListInsertAfter(numsList, node 1, node 4)

numsList:

Check Show answer

4) numsList: 77

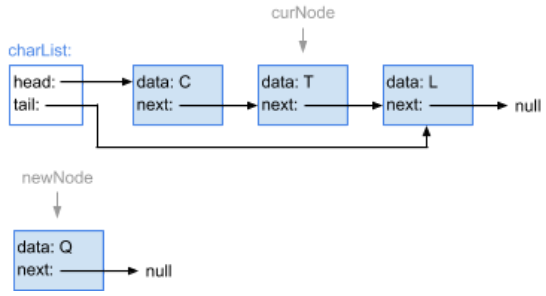
ListInsertAfter(numsList, node 77, node 32)
ListInsertAfter(numsList, node 32, node 50)
ListInsertAfter(numsList, node 32, node 46)

numsList:

Check Show answer

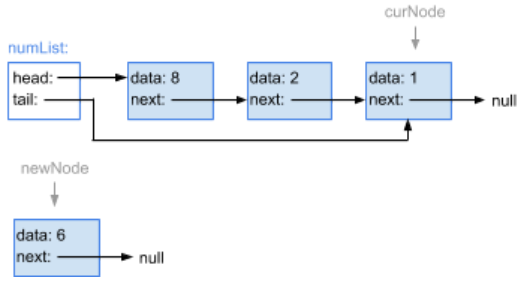
PARTICIPATION ACTIVITY 3.3.3: Singly-linked list insert-after algorithm.

1) ListInsertAfter(charList, node T, node Q) assigns newNode's next pointer with _____.



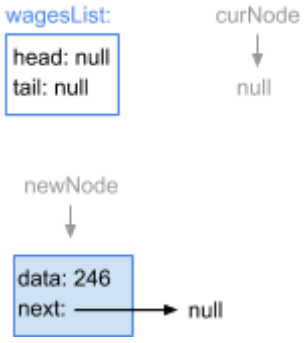
- curNode⋯→next
- charList's head node
- null

2) ListInsertAfter(numList, node 1, node 6) executes which statement?



- `list⋯→head = newNode`
- `newNode⋯→next = curNode⋯→next`
- `list⋯→tail⋯→next = newNode`

3) ListInsertAfter(wagesList, list head, node 246) executes which statement?



- `list⋯→head = newNode`
- `list⋯→tail⋯→next = newNode`
- `curNode⋯→next = newNode`

CHALLENGE ACTIVITY 3.3.1: Singly-linked lists: Insert.

Start

numList: 75, 97
ListInsertAfter(numList, node 97, node 44)
ListInsertAfter(numList, node 44, node 71)
ListInsertAfter(numList, node 44, node 41)

numList is now: Ex: 1, 2, 3 (comma between values)

Check Next

3.4 Singly-linked lists: Remove

Given a specified existing node in a singly-linked list, the ***RemoveAfter*** operation removes the node after the specified list node. The existing node must be specified because each node in a singly-linked list only maintains a pointer to the next node.

The existing node is specified with the curNode parameter. If curNode is null, RemoveAfter removes the list's first node. Otherwise, the algorithm removes the node after curNode.

- *Remove list's head node (special case):* If curNode is null, the algorithm points sucNode to the head node's next node, and points the list's head pointer to sucNode. If sucNode is null, the only list node was removed, so the list's tail pointer is pointed to null (indicating the list is now empty).
- *Remove node after curNode:* If curNode's next pointer is not null (a node after curNode exists), the algorithm points sucNode to the node after curNode's next node. Then curNode's next pointer is pointed to sucNode. If sucNode is null, the list's tail node was removed, so the algorithm points the list's tail pointer to curNode (the new tail node).

PARTICIPATION ACTIVITY 3.4.1: Singly-linked list: Node removal.

Animation content:

undefined

Animation captions:

1. If curNode is null, the list's head node is removed.
2. The list's head pointer is pointed to the list head's successor node.
3. If node exists after curNode exists, that node is removed. sucNode points to node after the next node (i.e., the next next node).
4. curNode's next pointer is pointed to sucNode.
5. If sucNode is null, the list's tail node was removed. curNode is now the list tail node.
6. If list's tail node is removed, curNode's next pointer is null.
7. If list's tail node is removed, the list's tail pointer is pointed to curNode.

PARTICIPATION ACTIVITY 3.4.2: Removing nodes from a singly-linked list.

Type the list after the given operations. Type the list as: 4, 19, 3

1) numsList: 2, 5, 9

ListRemoveAfter(numsList, node 5)

numsList:

Check Show answer

2) numsList: 3, 57, 28, 40

ListRemoveAfter(numsList, null)

numsList:

Check Show answer

3) numsList: 9, 4, 11, 7

ListRemoveAfter(numsList, node 11)

numsList:

Check Show answer

4) numsList: 10, 20, 30, 40, 50, 60

ListRemoveAfter(numsList, node 40)
ListRemoveAfter(numsList, node 20)

numsList:

Check Show answer

5) numsList: 91, 80, 77, 60, 75

ListRemoveAfter(numsList, node 60)
ListRemoveAfter(numsList, node 77)
ListRemoveAfter(numsList, null)

numsList:

Check Show answer

PARTICIPATION ACTIVITY 3.4.3: ListRemoveAfter algorithm execution: Intermediate node.

Given numList, ListRemoveAfter(numList, node 55) executes which of the following statements?

1) sucNode = list⋯→head⋯→next

- Yes
- No

2) curNode⋯→next = sucNode

- Yes

- No

3) list⋯→head = sucNode

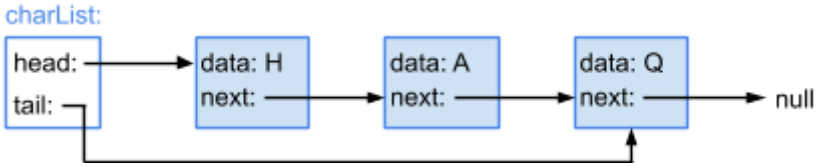
- Yes
- No

4) list⋯→tail = curNode

- Yes
- No

PARTICIPATION ACTIVITY 3.4.4: ListRemoveAfter algorithm execution: List head node.

Given charList, ListRemoveAfter(charList, null) executes which of the following statements?



1) sucNode = list⋯→head⋯→next

- Yes
- No

2) curNode⋯→next = sucNode

- Yes
- No

3) list⋯→head = sucNode

- Yes
- No

4) list⋯→tail = curNode

- Yes
- No

CHALLENGE 3.4.1: Singly-linked lists: Remove.

ACTIVITY

Start

Given list: 4, 5, 9, 7, 1
What list results from the following operations?

ListRemoveAfter(list, node 5)
ListRemoveAfter(list, null)
ListRemoveAfter(list, node 7)

List items in order, from head to tail.

Ex: 25, 42, 12

1 2 3 4 5

Check Next

3.5 Linked list search

Given a key, a ***search*** algorithm returns the first node whose data matches that key, or returns null if a matching node was not found. A simple linked list search algorithm checks the current node (initially the list's head node), returning that node if a match, else pointing the current node to the next node and repeating. If the pointer to the current node is null, the algorithm returns null (matching node was not found).

PARTICIPATION ACTIVITY 3.5.1: Singly-linked list: Searching.

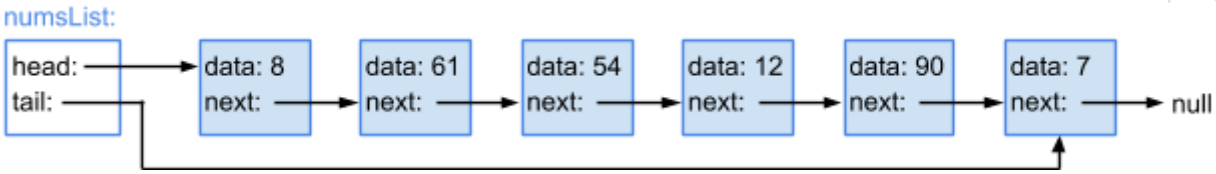
Animation content:

undefined

Animation captions:

1. Search starts at list's head node. If node's data matches key, matching node is returned.
2. If no matching node is found, null is returned.

PARTICIPATION ACTIVITY 3.5.2: ListSearch algorithm execution.



1) How many nodes will ListSearch visit when searching for 54?

Check Show answer

2) How many nodes will ListSearch visit when searching for 48?

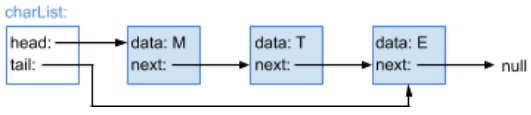
Check Show answer

3) What value does ListSearch return if the search key is not found?

Check Show answer

PARTICIPATION ACTIVITY 3.5.3: Searching a linked-list.

1) ListSearch(charList, E) first assigns curNode to _____.

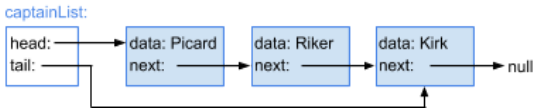


- Node M
-

Node T

- Node E

2) For ListSearch(captainList, Sisko), after checking node Riker, to which node is curNode pointed?

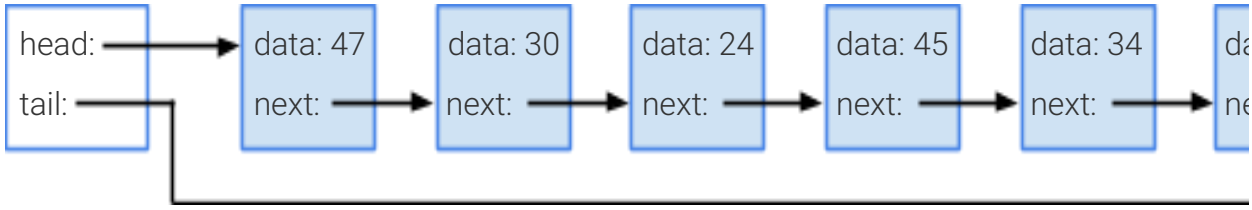


- node Riker
- node Kirk

CHALLENGE ACTIVITY 3.5.1: Linked list search.

Start

numList:



ListSearch(numList, 26) points the current pointer to node Ex: 9 after checking node 47.

ListSearch(numList, 26) will make comparisons.

1 2

Check Next

3.6 Array-based lists

Array-based lists

An ***array-based list*** is a list ADT implemented using an array. An array-based list supports the common list ADT operations, such as append, prepend, insert after, remove, and search.

In many programming languages, arrays have a fixed size. An array-based list implementation will dynamically allocate the array as needed as the number of elements changes. Initially, the array-based list implementation allocates a fixed size array and use a length variable to keep track of how many array elements are in use. The list starts with a default allocation size, greater than or equal to 1. A default size of 1 to 10 is common.

Given a new element, the ***append*** operation for an array-based list of length X inserts the new element at the end of the list, or at index X.

PARTICIPATION ACTIVITY 3.6.1: Appending to array-based lists.

Animation captions:

1. An array of length 4 is initialized for an empty list. Variables store the allocation size of 4 and list length of 0.
2. Appending 45 uses the first entry in the array, and the length is incremented to 1.
3. Appending 84, 12, and 78 uses the remaining space in the array.

PARTICIPATION ACTIVITY 3.6.2: Array-based lists.

1) The length of an array-based list equals the list's array allocation size.
   - ○ True
   - ○ False

2) An item can be appended to an array-based list, provided the length is less than the array's allocated size.
   - ○ True
   - ○ False

3) An array-based list can have a default allocation size of 0.
   - ○ True
   - ○ False

Resize operation

An array-based list must be resized if an item is added when the allocation size equals the list length. A new array is allocated with a length greater than the existing array. Allocating the new array with twice the current length is a common approach. The existing array elements are then copied to the new array, which becomes the list's storage array.

Because all existing elements must be copied from 1 array to another, the resize operation has a runtime complexity of $O(N)$.

PARTICIPATION ACTIVITY 3.6.3: Array-based list resize operation.

Animation content:

undefined

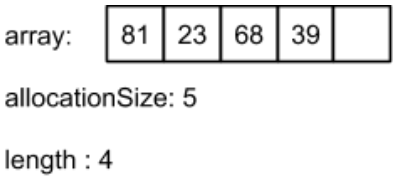
Animation captions:

1. The allocation size and length of the list are both 4. An append operation cannot add to the existing array.
2. To resize, a new array is allocated of size 8, and the existing elements are copied to the new array. The new array replaces the list's array.
3. 51 can now be appended to the array.

PARTICIPATION ACTIVITY 3.6.4: Array-based list resize operation.

Assume the following operations are executed on the list shown below:

ArrayListAppend(list, 98)
ArrayListAppend(list, 42)
ArrayListAppend(list, 63)



1) Which operation causes ArrayListResize to be called?
   - ArrayListAppend(list, 98)
   - ArrayListAppend(list, 42)
   - ArrayListAppend(list, 63)

2) What is the list's length after 63 is

appended?

- 5
- 7
- 10

3) What is the list's allocation size after 63 is appended?

- 5
- 7
- 10

Prepend and insert after operations

The ***Prepend*** operation for an array-based list inserts a new item at the start of the list. First, if the allocation size equals the list length, the array is resized. Then all existing array elements are moved up by 1 position, and the new item is inserted at the list start, or index 0. Because all existing array elements must be moved up by 1, the prepend operation has a runtime complexity of O(N).

The ***InsertAfter*** operation for an array-based list inserts a new item after a specified index. Ex: If the contents of `numbersList` is: 5, 8, 2, `ArrayListInsertAfter(numbersList, 1, 7)` produces: 5, 8, 7, 2. First, if the allocation size equals the list length, the array is resized. Next, all elements in the array residing after the specified index are moved up by 1 position. Then, the new item is inserted at index (specified index + 1) in the list's array. The InsertAfter operation has a best case runtime complexity of O(1) and a worst case runtime complexity of O(N).

InsertAt operation.

Array-based lists often support the InsertAt operation, which inserts an item at a specified index. Inserting an item at a desired index X can be achieved by using InsertAfter to insert after index X - 1.

PARTICIPATION ACTIVITY 3.6.5: Array-based list prepend and insert after operations.

Animation content:

`undefined`

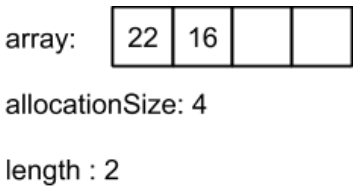
Animation captions:

1. To prepend 91, every array element is first moved up 1 index.
2. Item 91 is assigned at index 0.
3. Inserting item 36 after index 2 requires elements at indices 3 and higher to be moved up 1. Item 36 is inserted at index 3.

PARTICIPATION ACTIVITY 3.6.6: Array-based list prepend and insert after operations.

Assume the following operations are executed on the list shown below:

ArrayListPrepend(list, 76)
ArrayListInsertAfter(list, 1, 38)
ArrayListInsertAfter(list, 3, 91)



1) Which operation causes ArrayListResize to be called?
   - ArrayListPrepend(list, 76)
   - ArrayListInsertAfter(list, 1, 38)
   - ArrayListInsertAfter(list, 3, 91)

2) What is the list's allocation size after all operations have completed?
   - 5
   - 8
   - 10

3) What are the list's contents after all operations have completed?
   - 22, 16, 76, 38, 91
   - 76, 38, 22, 91, 16
   - 76, 22, 38, 16, 91

Search and removal operations

Given a key, the ***search*** operation returns the index for the first element whose data matches that key, or -1 if not found.

Given the index of an item in an array-based list, the ***remove-at*** operation removes the item at that index. When removing an item at index X, each item after index X is moved down by 1 position.

Both the search and remove operations have a worst case runtime complexity of O(N).

PARTICIPATION ACTIVITY 3.6.7: Array-based list search and remove-at operations.

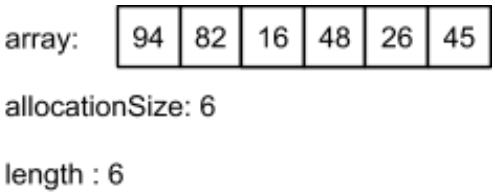
Animation content:

undefined

Animation captions:

1. The search for 84 compares against 3 elements before returning 2.
2. Removing the element at index 1 causes all elements after index 1 to be moved down to a lower index.
3. Decreasing the length by 1 effectively removes the last 51.
4. The search for 84 now returns 1.

PARTICIPATION ACTIVITY 3.6.8: Search and remove-at operations.



1) What is the return value from ArrayListSearch(list, 33)?

Check Show answer

2) When searching for 48, how many elements in the list will be compared with 48?

Check Show answer

3) ArrayListRemoveAt(list, 3) causes how many items to be moved down by 1 index?

Check Show answer

4) ArrayListRemoveAt(list, 5) causes how many items to be moved down by 1 index?

Check Show answer

PARTICIPATION ACTIVITY 3.6.9: Search and remove-at operations.

1) Removing at index 0 yields the best case runtime for remove-at.
   - True
   - False

2) Searching for a key that is not in the list yields the worst case runtime for search.
   - True
   - False

3) Neither search nor remove-at will resize the list's array.
   - True
   - False

CHALLENGE ACTIVITY 3.6.1: Array-based lists.

Start

numList: | 70 | 89 | |

allocationSize: 3
length: 2

If an item is added when the allocation size equals the array length, a new array with twice th current length is allocated.

Determine the length and allocation size of numList after each operation.

Operation	Length	Allocation size
ArrayListAppend(numList, 49)	Ex: 1	Ex:1
ArrayListAppend(numList, 56)		
ArrayListAppend(numList, 61)		
ArrayListAppend(numList, 30)		
ArrayListAppend(numList, 43)		

1 2 3 4

Check Next