4.1 Queue abstract data type (ADT)

Queue abstract data type

A ***queue*** is an ADT in which items are inserted at the end of the queue and removed from the front of the queue. The queue ***enqueue*** operation inserts an item at the end of the queue. The queue ***dequeue*** operation removes and returns the item at the front of the queue. Ex: After the operations "Enqueue 7", "Enqueue 14", and "Enqueue 9", "Dequeue" returns 7. A second "Dequeue" returns 14. A queue is referred to as a ***first-in first-out*** ADT. A queue can be implemented using a linked list or an array.

A queue ADT is similar to waiting in line at the grocery store. A person enters at the end of the line and exits at the front. British English actually uses the word "queue" in everyday vernacular where American English uses the word "line".

PARTICIPATION ACTIVITY 4.1.1: Queue ADT.

Animation content:

undefined

Animation captions:

1. A new queue named "wQueue" is created. Items are enqueued to the end of the queue.
2. Items are dequeued from the front of the queue.

PARTICIPATION ACTIVITY 4.1.2: Queue ADT.

1) Given numQueue: 5, 9, 1 (front is 5)
   What are the queue contents after the following enqueue operation?
   Type the queue as: 1, 2, 3

Enqueue(numQueue, 4)

Check Show answer

2) Given numQueue: 11, 22 (the front is 11)
What are the queue contents after the following enqueue operations?
Type the queue as: 1, 2, 3

Enqueue(numQueue, 28)
Enqueue(numQueue, 72)

Check Show answer

3) Given numQueue: 49, 3, 8
What is returned by the following dequeue operation?

Dequeue(numQueue)

Check Show answer

4) Given numQueue: 4, 8, 7, 1, 3
What is returned by the second dequeue operation?

Dequeue(numQueue)
Dequeue(numQueue)

Check Show answer

5) Given numQueue: 15, 91, 11

What is the queue after the following dequeue operation? Type the queue as: 1, 2, 3

Dequeue(numQueue)

Check Show answer

6) Given numQueue: 87, 21, 43
What are the queue's contents after the following operations? Type the queue as: 1, 2, 3

Dequeue(numQueue)
Enqueue(numQueue, 6)
Enqueue(numQueue, 50)
Dequeue(numQueue)

Check Show answer

Common queue ADT operations

Table 4.1.1: Some common operations for a queue ADT.

Operation	Description	Example starting with queue: 43, 12, 77 (front is 43)
Enqueue(queue, x)	Inserts x at end of the queue	Enqueue(queue, 56). Queue: 43, 12, 77, 56
Dequeue(queue)	Returns and removes item at front of queue	Dequeue(queue) returns: 43. Queue: 12, 77
Peek(queue)	Returns but does not remove item at the front of the queue	Peek(queue) return 43. Queue: 43, 12, 77
IsEmpty(queue)	Returns true if queue has no items	IsEmpty(queue) returns false.
GetLength(queue)	Returns the number of items in the queue	GetLength(queue) returns 3.

Note: Dequeue and Peek operations should not be applied to an empty queue; the resulting behavior may be undefined.

PARTICIPATION ACTIVITY 4.1.3: Common queue ADT operations.

1) Given rosterQueue: 400, 313, 270, 514, 119, what does GetLength(rosterQueue) return?
   - ○ 400
   - ○ 5

2) Which operation determines if the queue contains no items?

- IsEmpty
- Peek

3) Given parkingQueue: 1, 8, 3, what are the queue contents after Peek(parkingQueue)?

- 1, 8, 3
- 8, 3

4) Given parkingQueue: 2, 9, 4, what are the contents of the queue after Dequeue(parkingQueue)?

- 9, 4
- 2, 9, 4

5) Given that parkingQueue has no items (i.e., is empty), what does GetLength(parkingQueue) return?

- -1
- 0
- Undefined

CHALLENGE ACTIVITY 4.1.1: Queue ADT.

Start

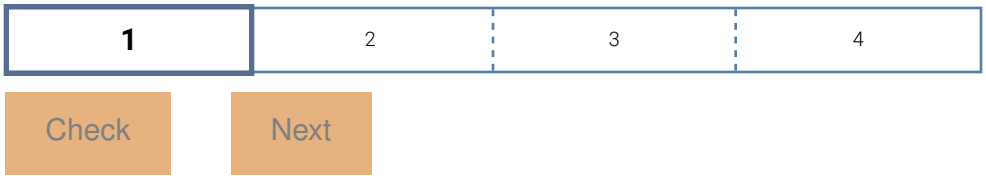
Given numQueue: 73, 68, 69
What are the queue's contents after the following operations?

Enqueue(numQueue, 17)
Dequeue(numQueue)

Ex: 1, 2, 3

After the above operations, what does GetLength(numQueue) return?

Ex: 8



4.2 Queues using linked lists

A queue is often implemented using a linked list, with the list's head node representing the queue's front, and the list's tail node representing the queue's end. Enqueueing an item is performed by creating a new list node, assigning the node's data with the item, and appending the node to the list. Dequeuing is performed by assigning a local variable with the head node's data, removing the head node from the list, and returning the local variable.

PARTICIPATION ACTIVITY 4.2.1: Queue implemented using a linked list.

Animation content:

`undefined`

Animation captions:

1. Enqueueing an item puts the item in a list node and appends the node to the list.
2. A dequeue stores the head node's data in a local variable, removes the list's head node, and returns the local variable.

PARTICIPATION ACTIVITY 4.2.2: Queue push and pop operations with a linked list.

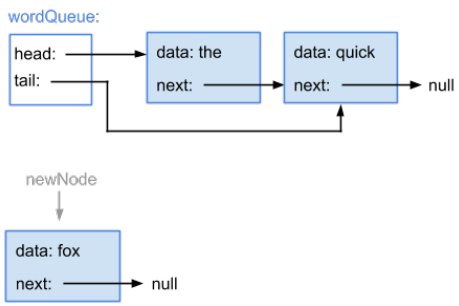
Assume the queue is implemented using a linked list.

1) If the head pointer is null, the queue _____.
   - is empty
   - is full
   - has at least one item

2) For the operation QueueDequeue(queue), what is the second parameter passed to ListRemoveAfter?
   - The list's head node
   - The list's tail node
   - null

3) For the operation QueueDequeue(queue), headData is assigned with the list _____ node's data.
   - head
   - tail

4) For QueueEnqueue(wordQueue, "fox"), which pointer is updated to point to the node?



- ○ wordQueue's head pointer
- ○ The head node's next pointer
- ○ The tail node's next pointer

CHALLENGE ACTIVITY 4.2.1: Queues using linked lists.

Start

Given an empty queue numQueue, what does the list head pointer point to? If the pointer is null, enter null.

Ex: 5 or null

What does the list tail pointer point to?

After the following operations:

QueueEnqueue(numQueue, 60)
QueueEnqueue(numQueue, 70)
QueueDequeue(numQueue)

What does the list head pointer point to?

What does the list tail pointer point to?

1 2

Check Next

4.3 List data structure

A common approach for implementing a linked list is using two data structures:

1. List data structure: A ***list data structure*** is a data structure containing the list's head and tail, and may also include additional information, such as the list's size.
2. List node data structure: The list node data structure maintains the data for each list element, including the element's data and pointers to the other list element.

A list data structure is not required to implement a linked list, but offers a convenient way to store the list's head and tail. When using a list data structure, functions that operate on a list can use a single parameter for the list's data structure to manage the list.

A linked list can also be implemented without using a list data structure, which minimally requires using separate list node pointer variables to keep track of the list's head.

PARTICIPATION ACTIVITY 4.3.1: Linked lists can be stored with or without a list data structure.

Animation content:

undefined

Animation captions:

1. A linked list can be maintained without a list data structure, but a pointer to the head and tail of the list must be stored elsewhere, often as local variables.
2. A list data structure stores both the head and tail pointers in one object.

PARTICIPATION ACTIVITY 4.3.2: Linked list data structure.

1) A linked list must have a list data structure.
   - ○ True
   - ○ False

2) A list data structure can have

additional information besides the head and tail pointers.

- ○ True
- ○ False

3) A linked list has O(n) space complexity, whether a list data structure is used or not.

- ○ True
- ○ False

4.4 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 4.4.1: 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 4.4.2: 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

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Common list ADT operations

Table 4.4.1: 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 4.4.3: 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

4.5 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 4.5.1: 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 4.5.2: 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 4.5.3: Array-based list resize operation.

Animation content:

undefined

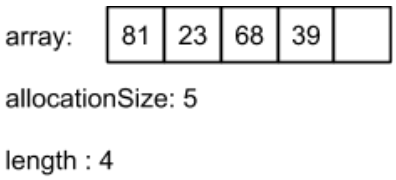
Animation captions:

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 4.5.4: 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 4.5.5: Array-based list prepend and insert after operations.

Animation content:

undefined

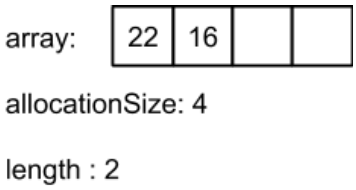
Animation captions:

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 4.5.6: 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 4.5.7: Array-based list search and remove-at operations.

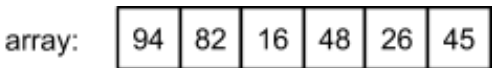
Animation content:

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 4.5.8: Search and remove-at operations.



allocationSize: 6

length : 6

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 4.5.9: 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 4.5.1: Array-based lists.

Start

numList: 20 | 51 | 25

allocationSize: 3
length: 3

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

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

Operation	Length	Allocation size
ArrayListAppend(numList, 79)	Ex: 1	Ex:1
ArrayListAppend(numList, 42)		
ArrayListAppend(numList, 84)		
ArrayListAppend(numList, 64)		
ArrayListAppend(numList, 57)		

1 2 3 4

Check Next

4.6 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 4.6.1: 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 4.6.2: Singly-linked list data structure.

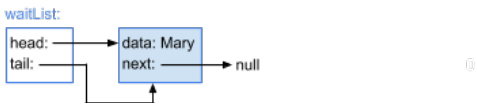
1) Given charList, C's next pointer value is _____.

Check Show answer

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

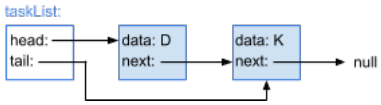
Check Show answer

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 4.6.3: 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.

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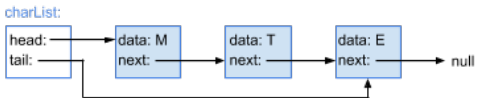
PARTICIPATION ACTIVITY 4.6.4: Appending a node to a singly-linked list.

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

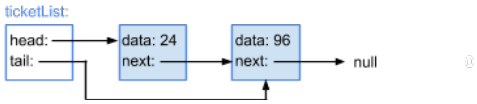


- M
- T
- E

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 4.6.5: Singly-linked list: Prepending a node.

Animation content:

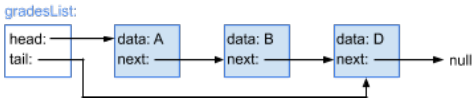
undefined

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 4.6.6: 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 4.6.1: Singly-linked lists.

4.7 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. 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 4.7.1: 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 4.7.2: 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)

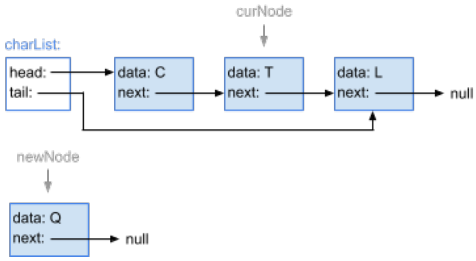
numsList:

Check Show answer

PARTICIPATION ACTIVITY 4.7.3: Singly-linked list insert-after algorithm.

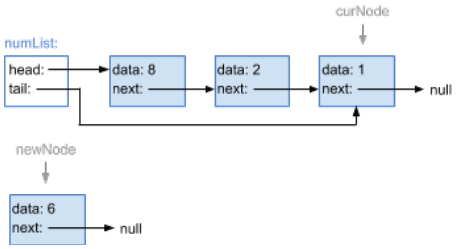
1) ListInsertAfter(charList, node T, node Q) assigns newNode's next

pointer with _____.



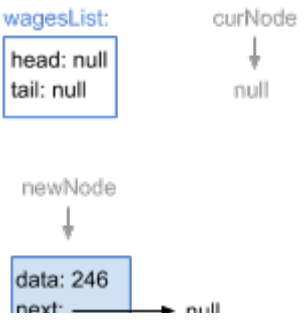
- curNode⇢next
- charList's head node
- null

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 4.7.1: Singly-linked lists: Insert.

4.8 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 4.8.1: 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 | 4.8.2: 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:

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

Check Show answer

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

numsList:

Check Show answer

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

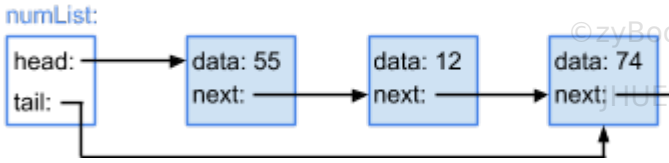
ListRemoveAfter(numsList, node 60)
ListRemoveAfter(numsList, node 77)
ListRemoveAfter(numsList, null)

numsList:

Check Show answer

PARTICIPATION ACTIVITY 4.8.3: 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

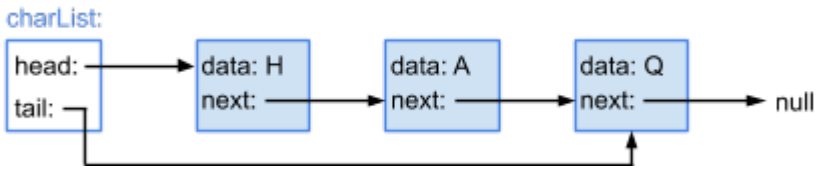
- Yes
- No

4) list⇢tail = curNode

- Yes
- No

PARTICIPATION ACTIVITY 4.8.4: 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 ACTIVITY 4.8.1: Singly-linked lists: Remove.

4.9 Linked list traversal

Linked list traversal

A ***list traversal*** algorithm visits all nodes in the list once and performs an operation on each node. A common traversal operation prints all list nodes. The algorithm starts by pointing a curNode pointer to the list's head node. While curNode is not null, the algorithm prints the current node, and then points curNode to the next node. After the list's tail node is visited, curNode is pointed to the tail node's next node, which does not exist. So, curNode is null, and the traversal ends. The traversal algorithm supports both singly-linked and doubly-linked lists.

Figure 4.9.1: Linked list traversal algorithm.

```
ListTraverse(list) {
   curNode = list→head // Start at head

   while (curNode is not null) {
      Print curNode's data
      curNode = curNode→next
   }
}
```


PARTICIPATION ACTIVITY 4.9.1: Singly-linked list: List traversal.

Animation content:

undefined

Animation captions:

1. Traverse starts at the list's head node.
2. curNode's data is printed, and then curNode is pointed to the next node.
3. After the list's tail node is printed, curNode is pointed to the tail node's next node, which does not exist.
4. The traversal ends when curNode is null.

PARTICIPATION ACTIVITY 4.9.2: List traversal.

1) ListTraverse begins with _____.

- ○ a specified list node
- ○ the list's head node
- ○ the list's tail node

2) Given numsList is: 5, 8, 2, 1. ListTraverse(numsList) visits _____ node(s).

- one
- two
- four

3) ListTraverse can be used to traverse a doubly-linked list.

- True
- False

Doubly-linked list reverse traversal

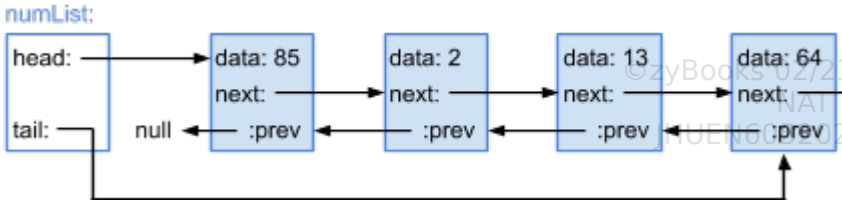
A doubly-linked list also supports a reverse traversal. A ***reverse traversal*** visits all nodes starting with the list's tail node and ending after visiting the list's head node.

Figure 4.9.2: Reverse traversal algorithm.

```
ListTraverseReverse(list) {
   curNode = list→tail // Start at tail

   while (curNode is not null) {
      Print curNode's data
      curNode = curNode→prev
   }
}
```

PARTICIPATION ACTIVITY 4.9.3: Reverse traversal algorithm execution.



1) ListTraverseReverse visits which node second?

- Node 2
- Node 1.3

2) ListTraverseReverse can be used to traverse a singly-linked list.

- True
- False

4.10 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 4.10.1: Singly-linked list: Searching.

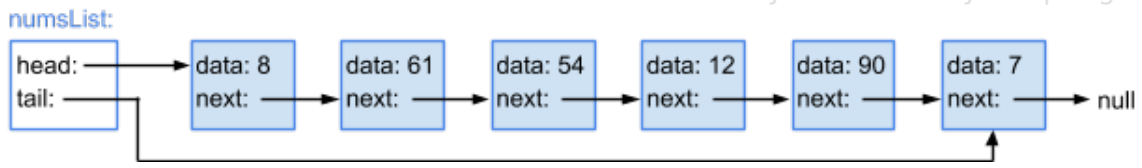
Animation content:

`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 4.10.2: 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?

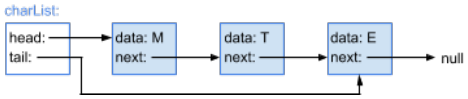
Check Show answer

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

Check Show answer

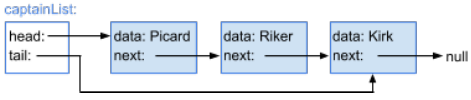
PARTICIPATION ACTIVITY 4.10.3: Searching a linked-list.

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

CHALLENGE ACTIVITY 4.10.1: Linked list search.

4.11 Linked lists: Recursion

Forward traversal

Forward traversal through a linked list can be implemented using a recursive function that takes a node as an argument. If non-null, the node is visited first. Then, a recursive call is made on the node's next pointer, to traverse the remainder of the list.

The ListTraverse function takes a list as an argument, and searches the entire list by calling ListTraverseRecursive on the list's head.

PARTICIPATION ACTIVITY 4.11.1: Recursive forward traversal.

Animation content:

`undefined`

Animation captions:

1. ListTraverse begins traversal by calling the recursive function, ListTraverseRecursive, on the list's head.
2. The recursive function visits the node and calls itself for the next node.
3. Nodes 19 is visited and an additional recursive call visits node 41. The last recursive call encounters a null node and stops.

PARTICIPATION ACTIVITY 4.11.2: Forward traversal in a linked list with 10 nodes.

1) If ListTraverse is called to traverse

a list with 10 nodes, how many calls to ListTraverseRecursive are made?

- 9
- 10
- 11

PARTICIPATION ACTIVITY 4.11.3: Forward traversal concepts.

1) ListTraverseRecursive works for both singly-linked and doubly-linked lists.
   - True
   - False

2) ListTraverseRecursive works for an empty list.
   - True
   - False

Searching

A recursive linked list search is implemented similar to forward traversal. Each call examines 1 node. If the node is null, then null is returned. Otherwise, the node's data is compared to the search key. If a match occurs, the node is returned, otherwise the remainder of the list is searched recursively.

Figure 4.11.1: ListSearch and ListSearchRecursive functions.

```
ListSearch(list, key) {
   return ListSearchRecursive(key, list→head)
}

ListSearchRecursive(key, node) {
   if (node is not null) {
      if (node→data == key) {
         return node
      }
      return ListSearchRecursive(key, node→next)
   }
   return null
}
```


PARTICIPATION ACTIVITY 4.11.4: Searching a linked list with 10 nodes.

Suppose a linked list has 10 nodes.

1) When more than 1 of the list's nodes contains the search key, ListSearch returns _____ node containing the key.
   - ○ the first
   - ○ the last
   - ○ a random

2) Calling ListSearch results in a minimum of _____ calls to ListSearchRecursive.
   - ○ 1
   - ○ 2
   - ○ 10
   - ○ 11

3) When the key is not found, ListSearch returns _____.

- the list's head
- the list's tail
- null

Reverse traversal

Forward traversal visits a node first, then recursively traverses the remainder of the list. If the order is swapped, such that the recursive call is made first, the list is traversed in reverse order.

PARTICIPATION ACTIVITY 4.11.5: Recursive reverse traversal.

Animation content:

`undefined`

Animation captions:

1. ListTraverseReverse is called to traverse the list. Much like a forward traversal, ListTraverseReverseRecursive is called for the list's head.
2. The recursive call on node 19 is made before visiting node 23.
3. Similarly, the recursive call on node 41 is made before visiting node 19, and the recursive call on null is made before visiting node 41.
4. The recursive call with the null node argument takes no action and is the first to return.
5. Execution returns to the line after the ListTraverseReverseRecursive(null) call. The node argument then points to node 41, which is the first node visited.
6. As the recursive calls complete, the remaining nodes are visited in reverse order. The last ListTraverseReverseRecursive call returns to ListTraverseReverse.
7. The entire list has been visited in reverse order.

PARTICIPATION ACTIVITY 4.11.6: Reverse traversal concepts.

Suppose ListTraverseReverse is called on the following list.

1) ListTraverseReverse passes _____ as the argument to ListTraverseReverseRecursive.

- node 67
- node 18
- null

2) ListTraverseReverseRecursive has been called for each of the list's nodes by the time the tail node is visited.

- True
- False

3) If ListTraverseReverseRecursive were called directly on node 91, the nodes visited would be: _____.

- node 91 and node 67
- node 18, node 46, and node 91
- node 18, node 46, node 91, and node 67

4.12 Deque abstract data type (ADT)

Deque abstract data type

A ***deque*** (pronounced "deck" and short for double-ended queue) is an ADT in which items

can be inserted and removed at both the front and back. The deque push-front operation inserts an item at the front of the deque, and the push-back operation inserts at the back of the deque. The pop-front operation removes and returns the item at the front of the deque, and the pop-back operation removes and returns the item at the back of the deque. Ex: After the operations "push-back 7", "push-front 14", "push-front 9", and "push-back 5", "pop-back" returns 5. A subsequent "pop-front" returns 9. A deque can be implemented using a linked list or an array.

PARTICIPATION ACTIVITY 4.12.1: Deque ADT.

Animation captions:

1. The "push-front 34" operation followed by "push-front 51" produces a deque with contents 51, 34.
2. The "push-back 19" operation pushes 19 to the back of the deque, yielding 51, 34, 19. "Pop-front" then removes and returns 51.
3. Items can also be removed from the back of the deque. The "pop-back" operation removes and returns 19.

PARTICIPATION ACTIVITY 4.12.2: Deque ADT.

Determine the deque contents after the following operations.

push-front 71, **push-front 68,** **push-front 97,** **pop-back,** **push-front 45**	**push-back 45,** **push-back 71,** **push-front 97,** **push-front 68,** **pop-back**	**push-front 97,** **push-back 71,** **pop-front,** **push-front 45,** **push-back 68**

45, 97, 68

45, 71, 68

68, 97, 45

Reset

Common deque ADT operations

In addition to pushing or popping at the front or back, a deque typically supports peeking at the front and back of the deck and determining the length. A ***peek*** operation returns an item in the deque without removing the item.

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Table 4.12.1: Common deque ADT operations.

Operation	Description	Example starting with deque: 59, 63, 19 (front is 59)
PushFront(deque, x)	Inserts x at the front of the deque	PushFront(deque, 41). Deque: 41, 59, 63, 19
PushBack(deque, x)	Inserts x at the back of the deque	PushBack(deque, 41). Deque: 59, 63, 19, 41
PopFront(deque)	Returns and removes item at front of deque	PopFront(deque) returns 59. Deque: 63, 19
PopBack(deque)	Returns and removes item at back of deque	PopBack(deque) returns 19. Deque: 59, 63
PeekFront(deque)	Returns but does not remove the item at the front of deque	PeekFront(deque) returns 59. Deque is still: 59, 63, 19
PeekBack(deque)	Returns but does not remove the item at the back of deque	PeekBack(deque) returns 19. Deque is still: 59, 63, 19
IsEmpty(deque)	Returns true if the deque is empty	IsEmpty(deque) returns false.
GetLength(deque)	Returns the number of items in the deque	GetLength(deque) returns 3.

PARTICIPATION ACTIVITY 4.12.3: Common queue ADT operations.

1) Given rosterDeque: 351, 814, 216, 636, 484, 102, what does GetLength(rosterDeque) return?

- 351
- 102
- 6

2) Which operation determines if the deque contains no items?

- IsEmpty
- PeekFront

3) Given jobsDeque: 4, 7, 5, what are the deque contents after PeekBack(jobsDeque)?

- 4, 7, 5
- 4, 7

4) Given jobsDeque: 3, 6, 1, 7, what are the contents of the deque after PopFront(jobsDeque)?

- 6, 1, 7
- 3, 6, 1, 7

5) Given that jobsDeque is empty, what does GetLength(jobsDeque) return?

- -1
- 0
- Undefined

CHALLENGE ACTIVITY 4.12.1: Deque ADT.