5.1 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 5.1.1: 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 5.1.2: 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 5.1.1: 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 5.1.3: 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

5.2 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 5.2.1: Singly-linked list: Each node points to the next node.

Animation content:

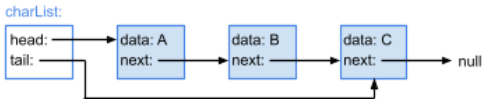
undefined

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 5.2.2: Singly-linked list data structure.

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

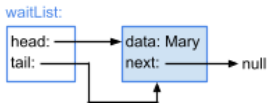


Check Show answer

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 node 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 5.2.3: Singly-linked list: Appending a node.

Animation content:

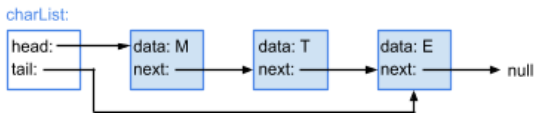
undefined

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 5.2.4: Appending a node to a singly-linked list.

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

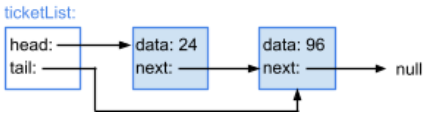


- M
- T
- E

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 5.2.5: Singly-linked list: Prepending a node.

Animation content:

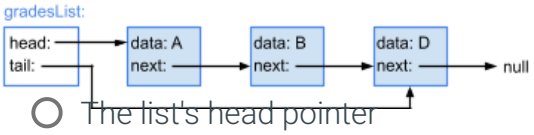
undefined

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 5.2.6: 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 5.2.1: Singly-linked lists.

489394.3384924.qx3zqy7

Start

What is numList after the following operations?

numList = new List

ListAppend(numList, node 73)
ListAppend(numList, node 96)

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

Check Next

5.3 List data structure

This section has been set as optional by your instructor.

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 5.3.1: 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 5.3.2: 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

5.4 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 5.4.1: 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 5.4.2: 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

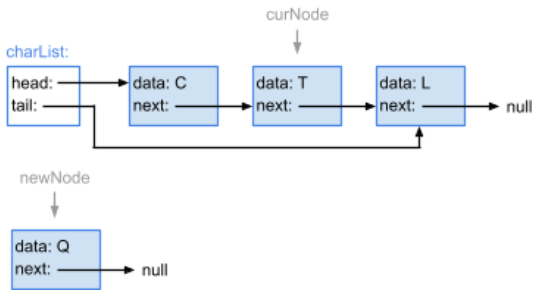
ListInsertAfter(numsList, node 77, node 32)
ListInsertAfter(numsList, node 32, node 50)
ListInsertAfter(numsList, node 32, node 46)

numsList:

Check Show answer

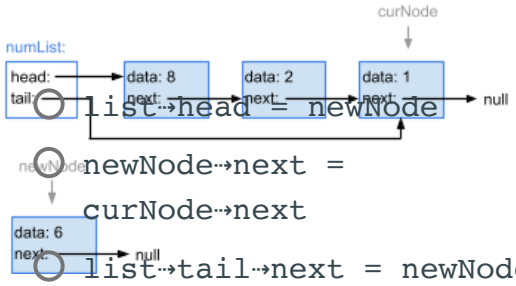
PARTICIPATION ACTIVITY 5.4.3: Singly-linked list insert-after algorithm.

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



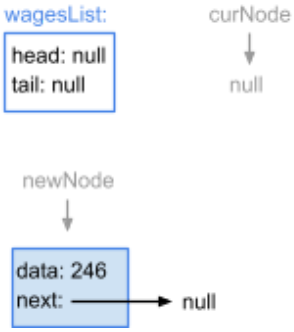
- curNode⇢next
- charList's head node
- null

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 5.4.1: Singly-linked lists: Insert.

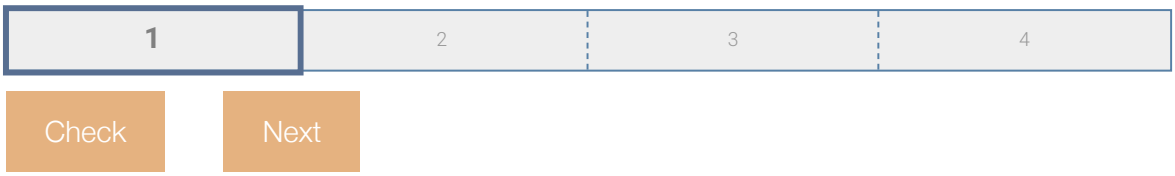
489394.3384924.qx3zqy7

Start

What is numList after the following operations?

numList: 62, 60
ListInsertAfter(numList, node 62, node 27)
ListInsertAfter(numList, node 27, node 95)
ListInsertAfter(numList, node 27, node 75)

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



5.5 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 5.5.1: 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 5.5.2: 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 5.5.3: 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

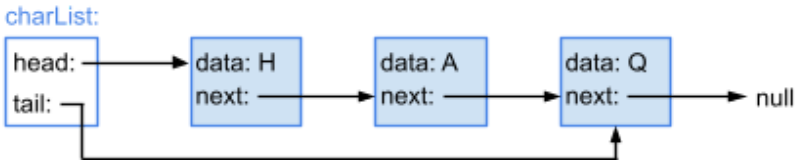
- Yes
- No

4) list⇢tail = curNode

- Yes
- No

PARTICIPATION ACTIVITY 5.5.4: 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 5.5.1: Singly-linked lists: Remove.

489394.3384924.qx3zqy7

Start

Given list: 9, 5, 4, 1, 2
What list results from the following operations?

ListRemoveAfter(list, node 1)
ListRemoveAfter(list, node 5)
ListRemoveAfter(list, null)

List items in order, from head to tail.

Ex: 25, 42, 12

1 2 3 4 5

Check Next

5.6 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 5.6.1: 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 5.6.2: 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?

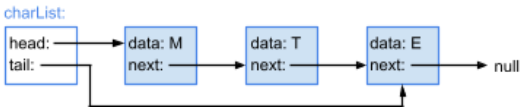
Check Show answer

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

Check Show answer

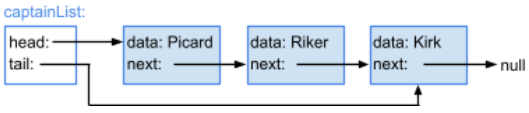
PARTICIPATION ACTIVITY 5.6.3: Searching a linked-list.

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?



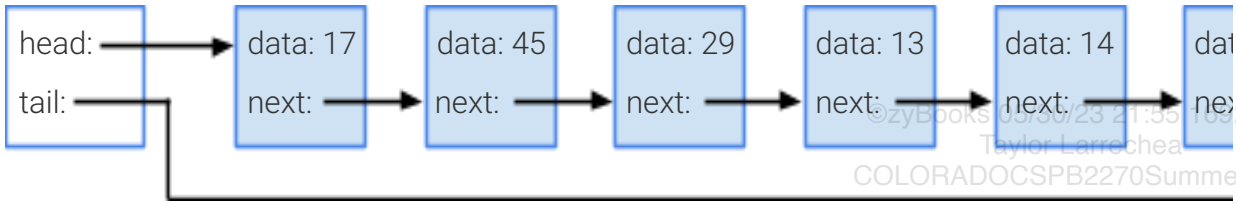
- node Riker
- node Kirk

CHALLENGE ACTIVITY 5.6.1: Linked list search.

489394.3384924.qx3zqy7

Start

numList:



ListSearch(numList, 14) points the current pointer to node Ex: 9 after checking node 45.

ListSearch(numList, 14) will make ____ comparisons.

1 2

Check Next

5.7 Doubly-linked lists

Doubly-linked list

A ***doubly-linked list*** is a data structure for implementing a list ADT, where each node has data, a pointer to the next node, and a pointer to the previous node. The list structure typically points to the first node and the last node. The doubly-linked list's first node is called the head, and the last node the tail.

A doubly-linked list is similar to a singly-linked list, but instead of using a single pointer to the next node in the list, each node has a pointer to the next and previous nodes. Such a list is called "doubly-linked" because each node has two pointers, or "links". A doubly-linked list is a type of ***positional list***: A list where elements contain pointers to the next and/or previous elements in the list.

PARTICIPATION ACTIVITY 5.7.1: Doubly-linked list data structure.

1) Each node in a doubly-linked list contains data and ____ pointer(s).

- one

- two

2) Given a doubly-linked list with nodes 20, 67, 11, node 20 is the _____.
   - head
   - tail

3) Given a doubly-linked list with nodes 4, 7, 5, 1, node 7's previous pointer points to node _____.
   - 4
   - 5

4) Given a doubly-linked list with nodes 8, 12, 7, 3, node 7's next pointer points to node _____.
   - 12
   - 3

Appending a node to a doubly-linked list

Given a new node, the ***Append*** operation for a doubly-linked list inserts the new node after the list's tail node. 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 to the new node, points the new node's previous pointer to the list's tail node, and points the list's tail pointer to the new node.

PARTICIPATION ACTIVITY 5.7.2: Doubly-linked list: Appending a node.

Animation content:

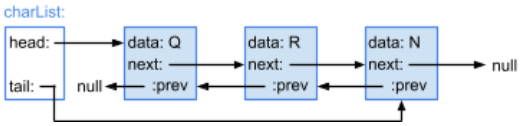
undefined

Animation captions:

1. Appending an item to an empty list updates 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.
3. newNode's previous pointer is pointed to the list's tail node.
4. The list's tail pointer is then pointed to the new node.

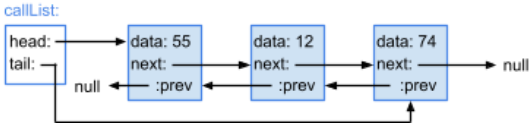
PARTICIPATION ACTIVITY 5.7.3: Doubly-linked list data structure.

1) ListAppend(charList, node F) inserts node F _____.



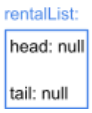
- after node Q
- before node N
- after node N

2) ListAppend(callList, node 5) executes which statement?



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

3) Appending node K to rentalList executes which of the following statements?



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

Prepending a node to a doubly-linked list

Given a new node, the ***Prepend*** operation of a doubly-linked list inserts the new node before the list's head node and points the head pointer to the new node.

- *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 list's head node, points the list head node's previous pointer to the new node, and then points the list's head pointer to the new node.

PARTICIPATION ACTIVITY 5.7.4: Doubly-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 new node's next pointer to the list's head node.
3. Prepending then points the head node's previous pointer to the new node.
4. Then the list's head pointer is pointed to the new node.

PARTICIPATION ACTIVITY 5.7.5: Prepending a node in a doubly-linked list.

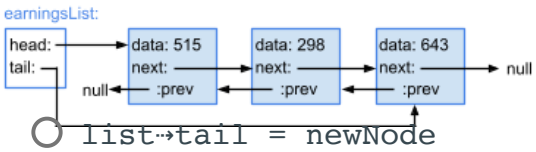
1) Prepending 29 to trainsList updates the list's head pointer to point to node _____.

- 4
- 29
- 31

2) ListPrepend(shoppingList, node Milk) updates the list's tail pointer.

- True
- False

3) ListPrepend(earningsList, node 977) executes which statement?



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

CHALLENGE ACTIVITY 5.7.1: Doubly-linked lists.

489394.3384924.qx3zqy7

Start

numList = new List
ListAppend(numList, node 31)
ListAppend(numList, node 98)
ListAppend(numList, node 13)
ListAppend(numList, node 55)

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

Which node has a null next pointer? Ex: 5

Which node has a null previous pointer? Ex: 5

1 2 3 4 5

Check Next

5.8 Doubly-linked lists: Insert

Given a new node, the ***InsertAfter*** operation for a doubly-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 first node:* If the list's head pointer is null (list is empty), 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 is not empty) and curNode points to the list's tail node, the new node is inserted after the tail node. The algorithm points the tail node's next pointer to the new node, points the new node's previous pointer to the list's tail node, and then points the list's tail pointer to the new node.
- *Insert in middle of list:* If the list's head pointer is not null (list is not empty) and curNode does not point to the list's tail node, the algorithm updates the current, new, and successor nodes' next and previous pointers to achieve the ordering {curNode newNode sucNode}, which requires four pointer updates: point the new node's next pointer to sucNode, point the new node's previous pointer to curNode, point curNode's next pointer to the new node, and point sucNode's previous pointer to the new node.

PARTICIPATION ACTIVITY 5.8.1: Doubly-linked list: Inserting nodes.

Animation content:

undefined

Animation captions:

1. Inserting a first node into the list points the list's head and tail pointers to the new node.
2. Inserting after the list's tail node points the tail node's next pointer to the new node.
3. Then the new node's previous pointer is pointed to the list's tail node. Finally, the list's tail pointer is pointed to the new node.
4. Inserting in the middle of a list points sucNode to curNode's successor (curNode's next node), then points newNode's next pointer to the successor node....
5. ...then points newNode's previous pointer to curNode...
6. ...and finally points curNode's next pointer to the new node.
7. Finally, points sucNode's previous pointer to the new node. At most, four pointers are updated to insert a new node in the list.

PARTICIPATION ACTIVITY 5.8.2: Inserting nodes in a doubly-linked list.

Given weeklySalesList: 12, 30
Show the node order after the following operations:

ListInsertAfter(weeklySalesList, list tail, node 8)
ListInsertAfter(weeklySalesList, list head, node 45)
ListInsertAfter(weeklySalesList, node 45, node 76)

If unable to drag and drop, refresh the page.

node 76 | node 45 | node 30 | node 8 | node 12

	Position 0 (list's head node)
	Position 1
	Position 2
	Position 3
	Position 4 (list's tail node)

Reset

CHALLENGE ACTIVITY 5.8.1: Doubly-linked lists: Insert.

489394.3384924.qx3zqy7

Start

What is numList after the following operations?

numList: 87, 17
ListInsertAfter(numList, node 17, node 89)
ListInsertAfter(numList, node 89, node 50)
ListInsertAfter(numList, node 89, node 91)

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

What node does node 91's next pointer point to?

What node does node 91's previous pointer point to?

1 2 3 4

Check Next

5.9 Doubly-linked lists: Remove

The ***Remove*** operation for a doubly-linked list removes a provided existing list node. curNode is a pointer to an existing list node. The algorithm first determines the node's successor (the next node) and predecessor (the previous node). The variable sucNode points to the node's successor, and the variable predNode points to the node's predecessor. The algorithm uses four separate checks to update each pointer:

- *Successor exists:* If the successor node pointer is not null (successor exists), the algorithm points the successor's previous pointer to the predecessor node.
- *Predecessor exists:* If the predecessor node pointer is not null (predecessor exists), the algorithm points the predecessor's next pointer to the successor node.
- *Removing list's head node:* If curNode points to the list's head node, the algorithm points the list's head pointer to the successor node.
- *Removing list's tail node:* If curNode points to the list's tail node, the algorithm points the list's tail pointer to the predecessor node.

When removing a node in the middle of the list, both the predecessor and successor nodes exist, and the algorithm updates the predecessor and successor nodes' pointers to achieve the ordering {predNode sucNode}. When removing the only node in a list, curNode points to both the list's head and tail nodes, and sucNode and predNode are both null. So, the algorithm points the list's head and tail pointers to null, making the list empty.

PARTICIPATION ACTIVITY 5.9.1: Doubly-linked list: Node removal.

Animation content:

undefined

Animation captions:

1. curNode points to the node to be removed. sucNode points to curNode's successor (curNode's next node). predNode points to curNode's predecessor (curNode's previous node).
2. sucNode's previous pointer is pointed to the node preceding curNode.
3. If curNode points to the list's head node, the list's head pointer is pointed to the successor node. With the pointers updated, curNode can be removed.
4. curNode points to node 5, which will be removed. sucNode points to node 2. predNode points node 4.
5. The predecessor node's next pointer is pointed to the successor node. The successor node's previous pointer is pointed to the predecessor node. With pointers updated, curNode can be removed.
6. curNode points to node 2, which will be removed. sucNode points to nothing (null). predNode points to node 4.

7. The predecessor node's next pointer is pointed to the successor node. If curNode points to the list's tail node, the list's tail pointer is assigned with predNode. With pointers updated, curNode can be removed.

PARTICIPATION ACTIVITY 5.9.2: Deleting nodes from a doubly-linked list.

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

1) numsList: 71, 29, 54

ListRemove(numsList, node 29)

numsList:

Check Show answer

2) numsList: 2, 8, 1

ListRemove(numsList, list tail)

numsList:

Check Show answer

3) numsList: 70, 82, 41, 120, 357, 66

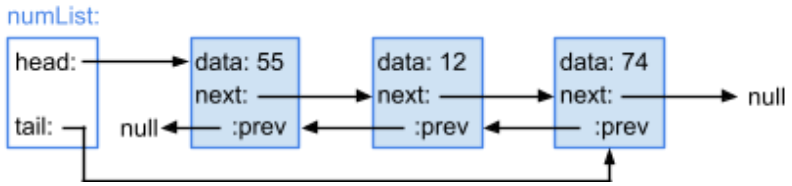
ListRemove(numsList, node 82)
ListRemove(numsList, node 357)
ListRemove(numsList, node 66)

numsList:

Check Show answer

PARTICIPATION ACTIVITY 5.9.3: ListRemove algorithm execution: Intermediate node.

Given numList, ListRemove(numList, node 12) executes which of the following statements?



1) sucNode⇢prev = predNode

- Yes
- No

2) predNode⇢next = sucNode

- Yes
- No

3) list⇢head = sucNode

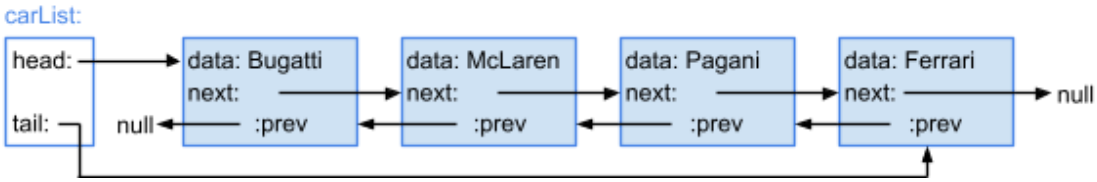
- Yes
- No

4) list⇢tail = predNode

- Yes
- No

PARTICIPATION ACTIVITY 5.9.4: ListRemove algorithm execution: List head node.

Given carList, ListRemove(carList, node Bugatti) executes which of the following statements?



1) sucNode⇢prev = predNode

- Yes
- No

2) predNode⇢next = sucNode

- Yes

- No

3) list⇢head = sucNode

- Yes
- No

4) list⇢tail = predNode

- Yes
- No

CHALLENGE ACTIVITY 5.9.1: Doubly-linked lists: Remove.

489394.3384924.qx3zqy7

Start

Given numList: 3, 5, 4, 1, 2, 8
What is numList after the following operations?

ListRemove(numList, node 8)
ListRemove(numList, node 3)
ListRemove(numList, node 1)

numList is now: Ex: 25, 42, 12

1 2 3 4 5

Check Next

5.10 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 5.10.1: 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 5.10.1: 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 5.10.2: 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

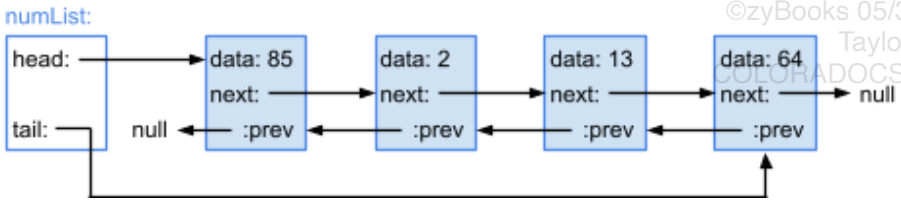
A doubly-linked list also supports a reverse traversal. A ***reverse traversal*** visits all nodes starting with the list's tail node and ending after visiting the list's head node.

Figure 5.10.2: 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 5.10.3: Reverse traversal algorithm execution.



1) ListTraverseReverse visits which node second?
   - Node 2

- Node 13

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

- True
- False

5.11 Sorting linked lists

Insertion sort for doubly-linked lists

Insertion sort for a doubly-linked list operates similarly to the insertion sort algorithm used for arrays. Starting with the second list element, each element in the linked list is visited. Each visited element is moved back as needed and inserted into the correct position in the list's sorted portion. The list must be a doubly-linked list, since backward traversal is not possible in a singly-linked list.

PARTICIPATION ACTIVITY 5.11.1: Sorting a doubly-linked list with insertion sort.

Animation content:

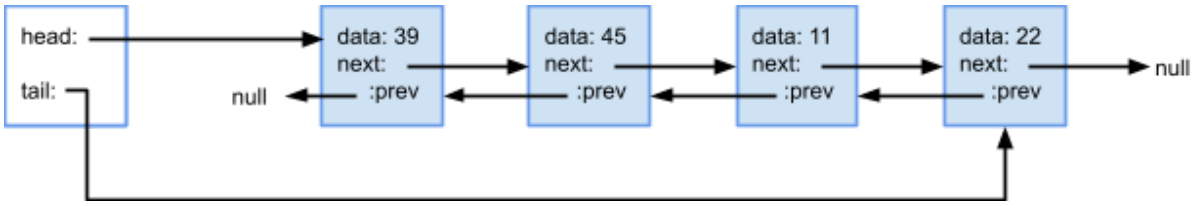
undefined

Animation captions:

1. The curNode pointer begins at node 91 in the list.
2. searchNode starts at node 81 and does not move because 81 is not greater than 91. Removing and re-inserting node 91 after node 81 does not change the list.
3. For node 23, searchNode traverses the list backward until becoming null. Node 23 is prepended as the new list head.
4. Node 49 is inserted after node 23, using ListInsertAfter.
5. Node 12 is inserted before node 23, using ListPrepend, to complete the sort.

PARTICIPATION ACTIVITY 5.11.2: Insertion sort for doubly-linked lists.

Suppose ListInsertionSortDoublyLinked is executed to sort the list below.



1) What is the first node that curNode will point to?

- Node 39
- Node 45
- Node 11

2) The ordering of list nodes is not altered when node 45 is removed and then inserted after node 39.

- True
- False

3) ListPrepend is called on which node(s)?

- Node 11 only
- Node 22 only
- Nodes 11 and 22

Algorithm efficiency

Insertion sort's typical runtime is O( ). If a list has N elements, the outer loop executes N - 1 times. For each outer loop execution, the inner loop may need to examine all elements in the sorted part. Thus, the inner loop executes on average times. So the total number of comparisons is proportional to , or O( ). In the best case scenario, the list is already sorted, and the runtime complexity is O( ).

Insertion sort for singly-linked lists

Insertion sort can sort a singly-linked list by changing how each visited element is inserted into the sorted portion of the list. The standard insertion sort algorithm traverses the list from the current element toward the list head to find the insertion position. For a singly-linked list, the insertion sort

algorithm can find the insertion position by traversing the list from the list head toward the current element.

Since a singly-linked list only supports inserting a node after an existing list node, the ListFindInsertionPosition algorithm searches the list for the insertion position and returns the list node after which the current node should be inserted. If the current node should be inserted at the head, ListFindInsertionPosition returns null.

PARTICIPATION ACTIVITY 5.11.3: Sorting a singly-linked list with insertion sort.

Animation content:

undefined

Animation captions:

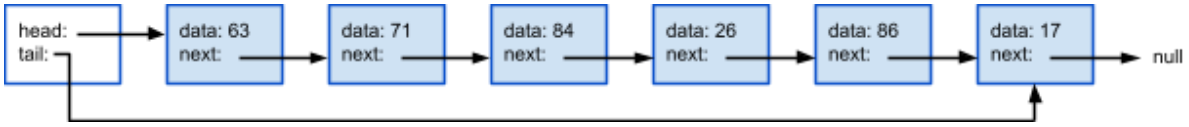
1. Insertion sort for a singly-linked list initializes curNode to point to the second list element, or node 56.
2. ListFindInsertionPosition searches the list from the head toward the current node to find the insertion position. ListFindInsertionPosition returns null, so Node 56 is prepended as the list head.
3. Node 64 is less than node 71. ListFindInsertionPosition returns a pointer to the node before node 71, or node 56. Then, node 64 is inserted after node 56.
4. The insertion position for node 87 is after node 71. Node 87 is already in the correct position and is not moved.
5. Although node 74 is only moved back one position, ListFindInsertionPosition compared node 74 with all other nodes' values to find the insertion position.

Figure 5.11.1: ListFindInsertionPosition algorithm.

```
ListFindInsertionPosition(list, dataValue) {
   curNodeA = null
   curNodeB = list→head
   while (curNodeB != null and dataValue >
curNodeB→data) {
      curNodeA = curNodeB
      curNodeB = curNodeB→next
   }
   return curNodeA
}
```


PARTICIPATION ACTIVITY 5.11.4: Sorting singly-linked lists with insertion sort.

Given ListInsertionSortSinglyLinked is called to sort the list below.



1) What is returned by the first call to ListFindInsertionPosition?

- null
- Node 63
- Node 71
- Node 84

2) How many times is ListPrepend called?

- 0
- 1
- 2

3) How many times is ListInsertAfter called?

- 0
- 1
- 2

Algorithm efficiency

The average and worst case runtime of ListInsertionSortSinglyLinked is O( ). The best case runtime is O( ), which occurs when the list is sorted in descending order.

Sorting linked-lists vs. arrays

Sorting algorithms for arrays, such as quicksort and heapsort, require constant-time access to arbitrary, indexed locations to operate efficiently. Linked lists do not allow indexed access, making for difficult adaptation of such sorting algorithms to operate on linked lists. The tables below provide a brief overview of the challenges in adapting array sorting algorithms for linked lists.

Table 5.11.1: Sorting algorithms easily adapted to efficiently sort linked lists.

Sorting algorithm	Adaptation to linked lists
Insertion sort	Operates similarly on doubly-linked lists. Requires searching from the head of the list for an element's insertion position for singly-linked lists.
Merge sort	Finding the middle of the list requires searching linearly from the head of the list. The merge algorithm can also merge lists without additional storage.

Table 5.11.2: Sorting algorithms difficult to adapt to efficiently sort linked lists.

Sorting algorithm	Challenge
Shell sort	Jumping the gap between elements cannot be done on a linked list, as each element between two elements must be traversed.
Quicksort	Partitioning requires backward traversal through the right portion of the array. Singly-linked lists do not support backward traversal.
Heap sort	Indexed access is required to find child nodes in constant time when percolating down.

PARTICIPATION ACTIVITY 5.11.5: Sorting linked-lists vs. sorting arrays.

1) What aspect of linked lists makes adapting array-based sorting algorithms to linked lists difficult?

- ○ Two elements in a linked list cannot be swapped in constant time.
- ○ Nodes in a linked list cannot be moved.

- Elements in a linked list cannot be accessed by index.

2) Which sorting algorithm uses a gap value to jump between elements, and is difficult to adapt to linked lists for this reason?

- Insertion sort
- Merge sort
- Shell sort

3) Why are sorting algorithms for arrays generally more difficult to adapt to singly-linked lists than to doubly-linked lists?

- Singly-linked lists do not support backward traversal.
- Singly-linked do not support inserting nodes at arbitrary locations.

5.12 Linked list dummy nodes

Dummy nodes

A linked list implementation may use a ***dummy node*** (or ***header node***): A node with an unused data member that always resides at the head of the list and cannot be removed. Using a dummy node simplifies the algorithms for a linked list because the head and tail pointers are never null.

An empty list consists of the dummy node, which has the next pointer set to null, and the list's head and tail pointers both point to the dummy node.

PARTICIPATION ACTIVITY 5.12.1: Singly-linked lists with and without a dummy node.

Animation captions:

1. An empty linked list without a dummy node has null head and tail pointers.
2. An empty linked list with a dummy node has the head and tail pointing to a node with null data.
3. Without the dummy node, a non-empty list's head pointer points to the first list item.

4. With a dummy node, the list's head pointer always points to the dummy node. The dummy node's next pointer points to the first list item.

PARTICIPATION ACTIVITY 5.12.2: Singly linked lists with a dummy node.

1) The head and tail pointers always point to the dummy node.
   - True
   - False

2) The dummy node's next pointer points to the first list item.
   - True
   - False

PARTICIPATION ACTIVITY 5.12.3: Condition for an empty list.

1) If myList is a singly-linked list with a dummy node, which statement is true when the list is empty?
   - `myList→head == null`
   - `myList→tail == null`
   - `myList→head == myList→tail`

Singly-linked list implementation

When a singly-linked list with a dummy node is created, the dummy node is allocated and the list's head and tail pointers are set to point to the dummy node.

List operations such as append, prepend, insert after, and remove after are simpler to implement compared to a linked list without a dummy node, since a special case is removed from each implementation. ListAppend, ListPrepend, and ListInsertAfter do not need to check if the list's head is null, since the list's head will always point to the dummy node. ListRemoveAfter does not need a special case to allow removal of the first list item, since the first list item is after the dummy node.

Figure 5.12.1: Singly-linked list with dummy node: append, prepend, insert after, and remove after operations.

```
ListAppend(list, newNode) {
   list→tail→next = newNode
   list→tail = newNode
}


ListPrepend(list, newNode) {
   newNode→next = list→head→next
   list→head→next = newNode
   if (list→head == list→tail) { // empty list
      list→tail = newNode;
   }
}


ListInsertAfter(list, curNode, newNode) {
   if (curNode == list→tail) { // Insert after tail
      list→tail→next = newNode
      list→tail = newNode
   }
   else {
      newNode→next = curNode→next
      curNode→next = newNode
   }
}


ListRemoveAfter(list, curNode) {
   if (curNode is not null and curNode→next is not
null) {
      sucNode = curNode→next→next
      curNode→next = sucNode

      if (sucNode is null) {
         // Removed tail
         list→tail = curNode
      }
   }
}
```


PARTICIPATION ACTIVITY 5.12.4: Singly-linked list with dummy node.

Suppose dataList is a singly-linked list with a dummy node.

1) Which statement removes the first item from the list?

   - `ListRemoveAfter(dataList, null)`
   - `ListRemoveAfter(dataList, dataList→head)`

- `ListRemoveAfter(dataList, dataList→tail)`

2) Which is a requirement of the ListPrepend function?

- The list is empty
- The list is not empty
- newNode is not null

PARTICIPATION ACTIVITY 5.12.5: Singly-linked list with dummy node.

Suppose numbersList is a singly-linked list with items 73, 19, and 86. Item 86 is at the list's tail.

1) What is the list's contents after the following operations?

```
lastItem = numbersList→tail
ListAppend(numbersList, node 25)
ListInsertAfter(numbersList, lastItem, node 49)
```

- 73, 19, 86, 25, 49
- 73, 19, 86, 49, 25
- 73, 19, 25, 49, 86

2) Suppose the following statement is executed:

```
node19 = numbersList→head→next→next
```

Which subsequent operations swap nodes 73 and 19?

- ListPrepend(numbersList, node19)
- ListInsertAfter(numbersList, numbersList→head, node19)
- ListRemoveAfter(numbersList, numbersList→head→next) ListPrepend(numbersList, node19)

Doubly-linked list implementation

A dummy node can also be used in a doubly-linked list implementation. The dummy node in a doubly-linked list always has the prev pointer set to null. ListRemove's implementation does not allow removal of the dummy node.

Figure 5.12.2: Doubly-linked list with dummy node: append, prepend, insert after, and remove operations.

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Taylor Larrechea
COLORADOCSPB2270Summer2023

```
ListAppend(list, newNode) {
   list→tail→next = newNode
   newNode→prev = list→tail
   list→tail = newNode
}


ListPrepend(list, newNode) {
   firstNode = list→head→next

   // Set the next and prev pointers for newNode
   newNode→next = list→head→next
   newNode→prev = list→head

   // Set the dummy node's next pointer
   list→head→next = newNode

   // Set prev on former first node
   if (firstNode is not null) {
      firstNode→prev = newNode
   }
}


ListInsertAfter(list, curNode, newNode) {
   if (curNode == list→tail) { // Insert after
tail
      list→tail→next = newNode
      newNode→prev = list→tail
      list→tail = newNode
   }
   else {
      sucNode = curNode→next
      newNode→next = sucNode
      newNode→prev = curNode
      curNode→next = newNode
      sucNode→prev = newNode
   }
}


ListRemove(list, curNode) {
   if (curNode == list→head) {
      // Dummy node cannot be removed
      return
   }

   sucNode = curNode→next
   predNode = curNode→prev

   if (sucNode is not null) {
      sucNode→prev = predNode
   }

   // Predecessor node is always non-null
   predNode→next = sucNode

   if (curNode == list→tail) { // Removed tail
      list→tail = predNode
   }
}
```

}

PARTICIPATION ACTIVITY 5.12.6: Doubly-linked list with dummy node.

1) `ListPrepend(list, newNode)` is equivalent to `ListInsertAfter(list, list→head, newNode)`.
   - True
   - False

2) ListRemove's implementation must not allow removal of the dummy node.
   - True
   - False

3) `ListInsertAfter(list, null, newNode)` will insert newNode before the list's dummy node.
   - True
   - False

Dummy head and tail nodes

A doubly-linked list implementation can also use 2 dummy nodes: one at the head and the other at the tail. Doing so removes additional conditionals and further simplifies the implementation of most methods.

PARTICIPATION ACTIVITY 5.12.7: Doubly-linked list append and prepend with 2 dummy nodes.

Animation content:

undefined

Animation captions:

1. A list with 2 dummy nodes is initialized such that the list's head and tail point to 2 distinct nodes. Data is null for both nodes.
2. Prepending inserts after the head. The list head's next pointer is never null, even when the list is empty, because of the dummy node at the tail.
3. Appending inserts before the tail, since the list's tail pointer always points to the dummy node.

Figure 5.12.3: Doubly-linked list with 2 dummy nodes: insert after and remove operations.

```
ListInsertAfter(list, curNode, newNode) {
   if (curNode == list→tail) {
      // Can't insert after dummy tail
      return
   }

   sucNode = curNode→next
   newNode→next = sucNode
   newNode→prev = curNode
   curNode→next = newNode
   sucNode→prev = newNode
}

ListRemove(list, curNode) {
   if (curNode == list→head || curNode ==
list→tail) {
      // Dummy nodes cannot be removed
      return
   }

   sucNode = curNode→next
   predNode = curNode→prev

   // Successor node is never null
   sucNode→prev = predNode

   // Predecessor node is never null
   predNode→next = sucNode
}
```


Removing if statements from ListInsertAfter and ListRemove

The if statement at the beginning of ListInsertAfter may be removed in favor of having a precondition that curNode cannot point to the dummy tail node. Likewise, ListRemove can remove the if statement and have a precondition that curNode cannot point to either dummy node. If such preconditions are met, neither function requires any if statements.

PARTICIPATION ACTIVITY 5.12.8: Comparing a doubly-linked list with 1 dummy node vs. 2 dummy nodes.

For each question, assume 2 list types are available: a doubly-linked list with 1 dummy node at the list's head, and a doubly-linked list with 2 dummy nodes, one at the head and the other at the tail.

1) When list→head == list→tail is true in _____, the list is empty.

- a list with 1 dummy node
- a list with 2 dummy nodes
- either a list with 1 dummy node or a list with 2 dummy nodes

2) list→tail may be null in _____.

- a list with 1 dummy node
- a list with 2 dummy nodes
- neither list type

3) list→head→next is always non-null in _____.

- a list with 1 dummy node
- a list with 2 dummy nodes
- neither list type

5.13 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 5.13.1: 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 5.13.2: 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 5.13.3: 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 5.13.1: 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 5.13.4: 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 5.13.5: 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 5.13.6: 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

5.14 Circular lists

This section has been set as optional by your instructor.

A ***circular linked list*** is a linked list where the tail node's next pointer points to the head of the list, instead of null. A circular linked list can be used to represent repeating processes. Ex: Ocean water evaporates, forms clouds, rains down on land, and flows through rivers back into the ocean. The head of a circular linked list is often referred to as the *start* node.

A traversal through a circular linked list is similar to traversal through a standard linked list, but must terminate after reaching the head node a second time, as opposed to terminating when reaching null.

PARTICIPATION ACTIVITY 5.14.1: Circular list structure and traversal.

Animation content:

undefined

Animation captions:

1. In a circular linked list, the tail node's next pointer points to the head node.
2. In a circular doubly-linked list, the head node's previous pointer points to the tail node.
3. Instead of stopping when the "current" pointer is null, traversal through a circular list stops when current comes back to the head node.

PARTICIPATION ACTIVITY 5.14.2: Circular list concepts.

1) Only a doubly-linked list can be circular.

- True
- False

2) In a circular doubly-linked list with at least 2 nodes, where does the head node's previous pointer point to?

- List head
- List tail
- null

3) In a circular linked list with at least 2 nodes, where does the tail node's next pointer point to?

- List head
- List tail
- null

4) In a circular linked list with 1 node, the tail node's next pointer points to the tail.

- True
- False

5) The following code can be used to traverse a circular, doubly-linked list in reverse order.

```
CircularListTraverseReverse(tail)
{
   if (tail is not null) {
      current = tail
      do {
         visit current
         current =
current→previous
      } while (current != tail)
   }
}
```

- True
- False

5.15 Array-based lists

This section has been set as optional by your instructor.

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 uses 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 5.15.1: 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 5.15.2: Array-based lists.

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

2) 42 is appended to an array-based list with allocationSize = 8 and length = 4. Appending assigns the array at index _____ with 42.
   - ○ 4
   - ○ 8

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( ).

PARTICIPATION ACTIVITY 5.15.3: Array-based list resize operation.

Animation content:

undefined

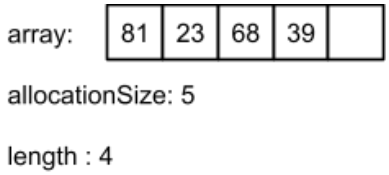
Animation captions:

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 5.15.4: 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( ).

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( ) and a worst case runtime complexity of O( ).

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 5.15.5: Array-based list prepend and insert after operations.

Animation content:

Step 1: Data members for a list are shown: array, allocationSize, and length.
"array:" label is followed by 8 boxes for the array's data. Entries at indices 0 to 4 are: 45, 84, 12, 78, 51. Entries at indices 5, 6, and 7 are empty.
The other two labels are "allocationSize: 8" and "length: 5".
ArrayListPrepend(list, 91) begins execution. The first if statement's condition is false. Then the for loop executes, moving items up in the array, yielding: 45, 45, 84, 12, 78, 51. Array boxes for indices 6 and 7 remain empty.

Step 2: Item 91 is assigned to index 0 in the array, yielding: 91, 45, 84, 12, 78, 51. Array boxes for indices 6 and 7 remain empty. Then length is incremented to 6.

Step 3: ArrayListInsertAfter(list, 2, 36) executes. The first if statement's condition is false, since 6 ≠ 8. The for loop moves items at indices 3, 4, and 5 up one, yielding: 91, 45, 84, 12, 12, 78, 51. Then 36 is assigned to index 3, yielding: 91, 45, 84, 36, 12, 78, 51. The array box for index 7 remains empty. Lastly, length is incremented to 7.

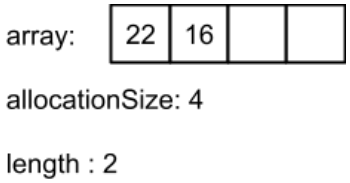
Animation captions:

1. To prepend 91, every array element is first moved up one index.
2. Item 91 is assigned to index 0 and length is incremented to 6.
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 5.15.6: 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( ).

PARTICIPATION ACTIVITY 5.15.7: Array-based list search and remove-at operations.

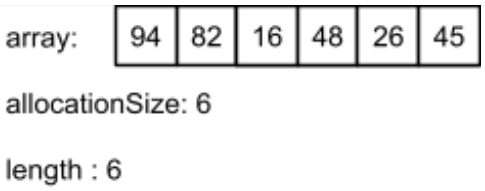
Animation content:

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 5.15.8: 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 5.15.9: 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 5.15.1: Array-based lists.

489394.3384924.qx3zqy7

Start

numList: | 23 | 26 | | |

allocationSize: 4
length: 2

Determine the length and allocation size of numList after each operation. If an item is added w the allocation size equals the array length, a new array with twice the current length is allocate

Operation	Length	Allocation size
ArrayListAppend(numList, 22)	Ex: 1	Ex:1
ArrayListAppend(numList, 69)		
ArrayListAppend(numList, 36)		
ArrayListAppend(numList, 51)		
ArrayListAppend(numList, 39)		

1 2 3 4

Check Next

5.16 Stack abstract data type (ADT)

This section has been set as optional by your instructor.

Stack abstract data type

A ***stack*** is an ADT in which items are only inserted on or removed from the top of a stack. The stack ***push*** operation inserts an item on the top of the stack. The stack ***pop*** operation removes and returns the item at the top of the stack. Ex: After the operations "Push 7", "Push 14", "Push 9", and "Push 5", "Pop" returns 5. A second "Pop" returns 9. A stack is referred to as a ***last-in first-out*** ADT. A stack can be implemented using a linked list, an array, or a vector.

PARTICIPATION ACTIVITY 5.16.1: Stack ADT.

Animation captions:

1. A new stack named "route" is created. Items can be pushed on the top of the stack.
2. Popping an item removes and returns the item from the top of the stack.

PARTICIPATION ACTIVITY 5.16.2: Stack ADT: Push and pop operations.

1) Given numStack: 7, 5 (top is 7).
Type the stack after the following push operation. Type the stack as: 1, 2, 3

Push(numStack, 8)

Check Show answer

2) Given numStack: 34, 20 (top is 34)
Type the stack after the following two push operations. Type the stack as: 1, 2, 3

Push(numStack, 11)
Push(numStack, 4)

Check Show answer

3) Given numStack: 5, 9, 1 (top is 5)
What is returned by the following pop operation?

Pop(numStack)

Check Show answer

4) Given numStack: 5, 9, 1 (top is 5)
What is the stack after the following pop operation? Type the stack as: 1, 2, 3

Pop(numStack)

Check Show answer

5) Given numStack: 2, 9, 5, 8, 1, 3 (top is 2).
What is returned by the second pop operation?

Pop(numStack)
Pop(numStack)

Check Show answer

6) Given numStack: 41, 8 (top is 41)
What is the stack after the following operations? Type the stack as: 1, 2, 3

Pop(numStack)
Push(numStack, 2)
Push(numStack, 15)
Pop(numStack)

Check Show answer

Common stack ADT operations

Table 5.16.1: Common stack ADT operations.

Operation	Description	Example starting with stack: 99, 77 (top is 99).
Push(stack, x)	Inserts x on top of stack	Push(stack, 44). Stack: 44, 99, 77
Pop(stack)	Returns and removes item at top of stack	Pop(stack) returns: 99. Stack: 77
Peek(stack)	Returns but does not remove item at top of stack	Peek(stack) returns 99. Stack still: 99, 77
IsEmpty(stack)	Returns true if stack has no items	IsEmpty(stack) returns false.
GetLength(stack)	Returns the number of items in the stack	GetLength(stack) returns 2.

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

PARTICIPATION ACTIVITY 5.16.3: Common stack ADT operations.

1) Given inventoryStack: 70, 888, -3, 2
What does GetLength(inventoryStack) return?

- 4
- 70

2) Given callStack: 2, 9, 4
What are the contents of the stack after Peek(callStack)?

- 2, 9, 4
- 9, 4

3) Given callStack: 2, 9, 4
What are the contents of the stack after Pop(callStack)?

- 2, 9, 4
- 9, 4

4) Which operation determines if the stack contains no items?

- Peek
- IsEmpty

5) Which operation should usually be preceded by a check that the stack is not empty?

- Pop
- Push

CHALLENGE ACTIVITY 5.16.1: Stack ADT.

489394.3384924.qx3zqy7

Start

Given numStack: 43, 98 (top is 43)

What is the stack after the operations?

Pop(numStack)
Push(numStack, 87)

Ex: 1, 2, 3

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

Ex: 5

1 2 3

Check Next

5.17 Stacks using linked lists

This section has been set as optional by your instructor.

A stack is often implemented using a linked list, with the list's head node being the stack's top. A push is performed by creating a new list node, assigning the node's data with the item, and prepending the node to the list. A pop is performed by assigning a local variable with the head node's data, removing the head node from the list, and then returning the local variable.

PARTICIPATION ACTIVITY 5.17.1: Stack implementation using a linked list.

Animation content:

undefined

Animation captions:

1. Pushing 45 onto the stack allocates a new node and prepends the node to the list.
2. Each push prepends a new node to the list.
3. A pop assigns a local variable with the list's head node's data, removes the head node, and returns the local variable.

PARTICIPATION ACTIVITY 5.17.2: Stack push and pop operations with a linked list.

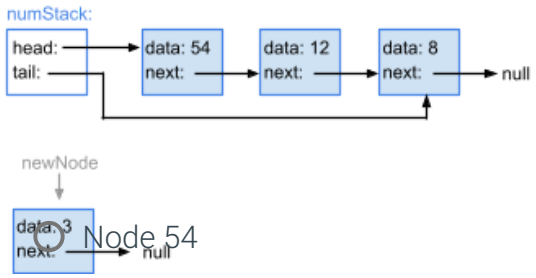
Assume the stack is implemented using a linked list.

1) An empty stack is indicated by a list head pointer value of _____.

- newNode
- null
- Unknown

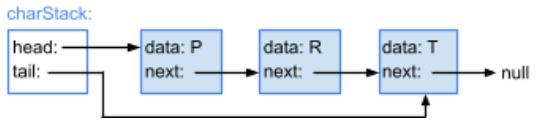
2) For StackPush(numStack, item 3), newNode's next pointer is pointed to

_____.



- Node 54
- Node 12
- null

3) The operation StackPop(charStack) will remove which node?



- Node P
- Node R
- Node T

4) StackPop returns list's head node.

- True
- False

CHALLENGE ACTIVITY 5.17.1: Stacks using linked lists.

489394.3384924.qx3zqy7

Start

Given an empty stack numStack,

What does the list head pointer point to? If the pointer is null, enter null.

Ex: 5 or null

After the operations, which node does the list head pointer point to?

```
StackPush(numStack, 17)
StackPush(numStack, 73)
StackPush(numStack, 57)
```

Ex: 5 or null

1 2 3

Check Next

5.18 Array-based stacks

Array-based stack storage

A stack can be implemented with an array. Two variables are needed in addition to the array:

- allocationSize: an integer for the array's allocated size.
- length: an integer for the stack's length.

The stack's bottom item is at `array[0]` and the top item is at `array[length - 1]`. If the stack is empty, length is 0.

PARTICIPATION ACTIVITY 5.18.1: Array-based stack storage.

Animation content:

undefined

Animation captions:

1. Stack 1's allocationSize and length are both 4. Array element 0 is at the stack's bottom. Array element 3 is at the stack's top.
2. Stack 2's length, 2, is less than allocationSize, 4. So elements at indices 2 and 3 are not part of the stack content.
3. The stack is empty when length is 0, regardless of array content.

Unbounded stack

An ***unbounded stack*** is a stack with no upper limit on length. An unbounded stack's length can increase indefinitely, so the stack's array allocation size must also be able to increase indefinitely.

PARTICIPATION ACTIVITY 5.18.2: Unbounded, array-based stack.

Animation content:

undefined

Animation captions:

1. The stack's initial allocation size is 1 and length is 0. So pushing 37 assigns array[0] with 37.
2. Pushing 88 occurs when allocationSize and length are both 1. So a new array is allocated, the existing entry is copied, and array[1] is assigned with 88.
3. Pushing 71 occurs when allocationSize and length are both 2. So a new array is allocated, the existing entries are copied, and array[2] is assigned with 71.

PARTICIPATION ACTIVITY 5.18.3: Unbounded stack.

Refer to the example above.

1) In the example above, when the array is reallocated, the size _____.
   - increases by 1
   - doubles
   - decreases by 1

2) When does a push operation resize the stack's array?
   - When `length == allocationSize`
   - When `length == allocationSize - 1`
   - Every push operation resizes the stack's array

3) In theory, an unbounded stack can grow in length indefinitely. In reality, the stack can _____.
   - also grow in length indefinitely
   - grow only until all distinct 32-bit integer values are pushed
   - grow only until the resize operation fails to allocate memory

Bounded stack

A ***bounded stack*** is a stack with a length that does not exceed a maximum value. The maximum is commonly the initial allocation size. Ex: A bounded stack with allocationSize = 100 cannot exceed a length of 100 items.

A bounded stack with a length equal to the maximum length is said to be ***full***.

PARTICIPATION ACTIVITY 5.18.4: Bounded, array-based stack.

Animation content:

undefined

Animation captions:

1. One implementation approach for a bounded stack is to allocate the array to the maximum length upon construction.
2. Three values push successfully.
3. The fourth push fails because length equals maxLength.
4. An alternate bounded stack implementation may distinguish allocation size and max length.
5. The first push assigns array[0] with 53. The second push must resize first, increasing allocationSize from 1 to 2.
6. Pushing 91 can now complete.
7. The next push must also resize. The min(allocationSize * 2, maxLength) = 3 is the new allocation size.
8. The next push fails because length equals maxLength.

PARTICIPATION ACTIVITY 5.18.5: Bounded stack - general implementation.

1) A bounded stack's maximum length and initial allocation size are always equal.
   - ○ True
   - ○ False

2) A bounded stack implementation may throw an exception if a push operation occurs when full.
   - ○ True
   - ○ False

3) Array-based stack implementations commonly reallocate when popping.

- True
- False

PARTICIPATION ACTIVITY 5.18.6: Bounded stack - two implementation approaches.

Consider two bounded stack implementation approaches.
Implementation A: Allocation size is provided at construction time and is the stack's maximum length.
Implementation B: Maximum length is specified at construction time. Default allocation size is 1.

1) Which implementation(s) may need to reallocate the array to push an item?

- Implementation A only
- Implementation B only
- Both
- Neither

2) Which implementation(s) may allow a push when `length == maxLength`?

- Implementation A only
- Implementation B only
- Neither

3) Which implementation(s) guarantee that both push and pop execute in worst-case O(1) time?

- Implementation A only
- Implementation B only
- Both
- Neither

Single implementation that allows bounded or unbounded

An array-based stack implementation can support both bounded and unbounded stack operations by using `maxLength` as follows:

- If `maxLength` is negative, the stack is unbounded.

- If `maxLength` is nonnegative, the stack is bounded.

The push operation does not allow a push when `length == maxLength`. The stack's length is always nonnegative, so:

- If `maxLength` is negative, the condition is never true. So all push operations are allowed, and therefore the stack is unbounded.
- If `maxLength` is nonnegative, the condition is true when the stack is full. So push operations are not allowed when full, and therefore the stack is bounded.

PARTICIPATION ACTIVITY 5.18.7: Stack push, resize, and pop operations.

Animation content:

undefined

Animation captions:

1. ArrayStackPush begins with a max length check. 0 ≠ 3, so the stack's length does not equal the maximum.
2. The stack's length, 0, does not equal allocation size, 1. So no resize is needed.
3. Array element 0 is assigned with 79, length is increased to 1, and true is returned.
4. When pushing 16, length and allocationSize are both 1, so ArrayStackResize() is called. The new allocation size is 1 * 2 = 2.
5. 79 is copied, the stack's array and allocationSize are reassigned, and then execution returns to ArrayStackPush to complete the push.
6. Length and allocation size are both 2, so pushing 54 requires a resize. min(2 * 2, 3) = 3 is the new allocation size.
7. The next push fails because length equals maxLength.
8. Popping 54 decreases the stack's length, but not allocation size. Popping does not resize the stack.

PARTICIPATION ACTIVITY 5.18.8: ArrayStackInitialize() function.

Assume the push, resize, and pop operations are implemented as in the animation above. Consider an ArrayStackInitialize() function that initializes the stack before any operations occur.

1) If `maxLength` is assigned with -1, then ArrayStackInitialize() may assign `allocationSize` with ____.

   ○ -1

- 0
- 2

2) If `maxLength` is assigned with 64, then ArrayStackInitialize() may assign `allocationSize` with ____.

- any integer
- any nonnegative integer
- any positive integer

PARTICIPATION ACTIVITY 5.18.9: Using ArrayStack functions for an unbounded stack.

Assume a stack is initialized as follows:

```
integerStack→allocationSize = 1
integerStack→array = Allocate array of size 1
integerStack→length = 0
integerStack→maxLength = -1
```

Assume the push, resize, and pop functions are implemented as in the animation above and that the operations below execute in question order.

1) `ArrayStackPush(integerStack, 21)` ____.

- does not change the stack and returns false
- causes an out-of-bounds write in the stack's array
- successfully pushes 21 and returns true

2) `ArrayStackPush(integerStack, 78)` ____.

- does not change the stack and returns false
- causes an out-of-bounds write in the stack's array
- resizes, pushes 78, and returns true

3) Two more calls to ArrayStackPush() occur. `integerStack`'s allocationSize,

length, and maxLength are _____, respectively.

- 2, 2, and -1
- 4, 4, and -1
- 4, 4, and 4

4) If each resize operation succeeds, the next 100 ArrayStackPush() operations succeed.

- True
- False

5) ArrayStackPop(), ArrayStackPush(), and ArrayStackResize() work for both bounded and unbounded stacks.

- True
- False

PARTICIPATION ACTIVITY 5.18.10: Array-based stack operation complexity.

1) For an unbounded stack, what operations take O(1) time in the *worst* case?

- ArrayStackPop() only
- ArrayStackPush() and ArrayStackPop()
- ArrayStackPush(), ArrayStackPop(), and ArrayStackResize()

2) For a bounded stack that does *not* resize, what operations take O(1) time in the *worst* case?

- ArrayStackPush() only
- ArrayStackPop() only
- ArrayStackPush() and ArrayStackPop()

5.19 Queue abstract data type (ADT)

This section has been set as optional by your instructor.

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 5.19.1: 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 5.19.2: 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 5.19.1: 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 5.19.3: 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 5.19.1: Queue ADT.

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Start

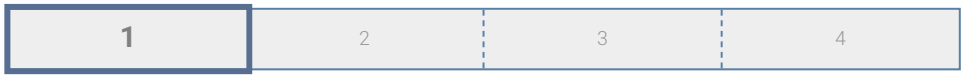
Given numQueue: 96, 24
What are the queue's contents after the following operations?

Enqueue(numQueue, 28)
Enqueue(numQueue, 40)

Dequeue(numQueue)
Dequeue(numQueue)

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

Ex: 8



Check Next

5.20 Queues using linked lists

This section has been set as optional by your instructor.

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 5.20.1: 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 5.20.2: 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

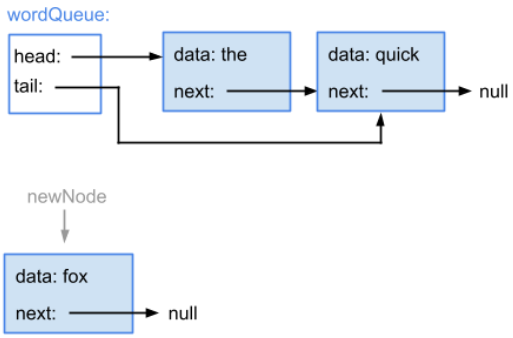
2) For the operation QueueDequeue(queue), what is the second parameter passed to ListRemoveAfter?

- 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 5.20.1: Queues using linked lists.

489394.3384924.qx3zqy7

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, 44)
QueueEnqueue(numQueue, 94)
QueueDequeue(numQueue)

What does the list head pointer point to?

What does the list tail pointer point to?

1 2

Check Next

5.21 Array-based queues

Array-based queue storage

A queue can be implemented with an array. Three variables are needed in addition to the array:

- allocationSize: an integer for the array's allocated size.
- length: an integer for the number of items in the queue.
- frontIndex: an integer for the queue's front item index.

The queue's content starts at `array[frontIndex]` and continues forward through `length` items. If the array's end is reached before encountering all items, remaining items are stored starting at index 0.

PARTICIPATION ACTIVITY 5.21.1: Array-based queue storage.

Animation content:

undefined

Animation captions:

1. Queue content starts at frontIndex. When frontIndex is 0 and length equals allocationSize, the queue's content matches the array's content: 78, 64, 16, 95.
2. If frontIndex is 2, then the queue's first two items are 16 and 95. Looping back to 0 gives the last two items, 78 and 64.
3. A length of 3 is one less than the allocation size, so 64 is not part of the queue.
4. The queue is empty when length is 0, regardless of array content.

PARTICIPATION ACTIVITY 5.21.2: Array-based queue storage.

A queue's array is [67, 19, 44, 38] and allocationSize is 4.

1) What is the queue's front item if frontIndex is 3 and length is 2?
   - ○ 67
   - ○ 44
   - ○ 38

2) What is the queue's back item if frontIndex is 0 and length is 3?
   - ○ 67
   - ○ 44
   - ○ 38

3) What is the queue's content if length is 4 and frontIndex is 1?
   - ○ (front) 67, 19, 44, 38 (back)
   - ○ (front) 19, 44, 38 (back)
   - ○ (front) 19, 44, 38, 67 (back)

Bounded vs. unbounded queue

A ***bounded queue*** is a queue with a length that does not exceed a specified maximum value. An additional variable, `maxLength`, is needed. `maxLength` is commonly assigned at construction time and does not change for the queue's lifetime. A bounded queue with a length equal to the maximum length is said to be ***full***.

An ***unbounded queue*** is a queue with a length that can grow indefinitely.

PARTICIPATION ACTIVITY 5.21.3: Bounded vs. unbounded queue.

Animation content:

undefined

Animation captions:

1. Three queues are created: the first unbounded, the second bounded with a maximum length of 2, and the third bounded with a maximum length of 4.
2. Enqueueing 51 then 88 yields the same results for each queue.
3. Enqueueing 73 fails for the full bounded queue, because the length and maximum length are both 2. Enqueueing 73 succeeds for the other two queues.
4. Similarly, enqueueing 47 succeeds for the first and third queues and fails for the second.
5. Both bounded queues now have a length equal to the maximum length. So enqueueing 24 succeeds only for the unbounded queue.

PARTICIPATION ACTIVITY 5.21.4: Bounded vs. unbounded queue.

1) _____ can be full.
   - Only a bounded queue
   - Only an unbounded queue
   - Both bounded and unbounded queues

2) A bounded queue implementation may throw an exception if an enqueue operation occurs when full.
   - True
   - False

3) The `maxLength` variable is needed _____.

- only for the bounded queue implementation
- only for the unbounded queue implementation
- for both the bounded and unbounded queue implementations

Flexible implementation and resize operation

An array-based queue implementation can support both bounded and unbounded queue operations by using `maxLength` as follows:

- If `maxLength` is negative, the queue is unbounded.
- If `maxLength` is nonnegative, the queue is bounded.

The resize operation allocates an array of larger size, commonly double the existing allocation size. If `maxLength` is nonnegative, the minimum of `maxLength` and double the current allocation size is used. Existing array entries are copied in such a way that the front index is reset to 0.

PARTICIPATION ACTIVITY 5.21.5: Array-based queue resize operation.

Animation content:

undefined

Animation captions:

1. maxLength = 4, so queue1 is bounded. length and allocationSize are both 3, so queue1 is full.
2. frontIndex is 1, so queue1's content from front to back is: 16, 53, 97.
3. Resizing queue1 begins with computing newSize. Double the current allocation size is 6. But maxLength is 4, which is nonnegative and less than 6. So 4 is used instead.
4. The new array is allocated. The first element is at index 1 in the existing array and is copied to index 0 in the new array.
5. Remaining elements are copied. Then array, allocationSize, and frontIndex are reassigned.
6. queue2's maxLength is -1 and maxLength is never reassigned. So when resizing, the condition queue⋯→maxLength >= 0 is always false.
7. So queue2 is unbounded, and each resize doubles the allocation size.

PARTICIPATION ACTIVITY 5.21.6: Flexible implementation and resize operation.

Consider queueA with variables:

```
allocationSize: 4
array: [73, 91, 87, 62]
frontIndex: 2
length: 4
maxLength: -1
```

1) queueA is _____.

- bounded and full
- bounded and not full
- unbounded

2) After executing `ArrayQueueResize(queueA)`, queueA's allocation size is _____.

- -1
- 4
- 8

3) After executing `ArrayQueueResize(queueA)`, `queueA.queue_list`'s first four elements are _____.

- 73, 91, 87, 62
- 87, 62, 73, 91

4) Can one of queueA's initial variables be changed such that executing `ArrayQueueResize(queueA)` makes queueA's allocation size 6?

- Yes, if `maxLength` were initially 6
- Yes, if `allocationSize` were initially 6
- No

Enqueue and dequeue operations

An enqueue operation:

1. Compares `length` and `maxLength`. If equal, the queue is full and so no change occurs and false is returned.
2. Compares `length` and `allocationSize`. If equal, a resize operation occurs.
3. Computes the enqueued item's index as `(frontIndex + length) % allocationSize` and assigns to the array at that index. Ex: Enqueueing 42 into a queue with frontIndex 2, length 3, and

allocationSize 8 assigns the queue array at index (2 + 3) % 8 = 5 with 42.
4. Increments `length` and then returns true.

A dequeue operation:

1. Makes a copy of the array item at `frontIndex`.
2. Decrements `length`.
3. Increments `frontIndex`, resetting to 0 if the incremented value equals the allocation size.
4. Returns the array item from step 1.

PARTICIPATION ACTIVITY 5.21.7: Array-based queue enqueue and dequeue operations.

Animation content:

undefined

Animation captions:

1. numQueue is an empty queue with allocationSize = 1. Enqueuing 42 starts by comparing length against maxLength, then allocation size.
2. array[0] is assigned with 42, length is incremented, and true is returned.
3. When enqueueing 89, a resize occurs first. Then array[1] is assigned with 89.
4. Enqueueing 71 resizes again, increasing allocationSize to 4. Then 64 is enqueued without resizing.
5. frontIndex = 0, so the dequeue operation begins by assigning toReturn with array[0]. Length is decremented to 3, frontIndex is reassigned with 1, and 42 is returned.
6. 89 is dequeued similarly.
7. 91 is enqueued at index 0.

PARTICIPATION ACTIVITY 5.21.8: Enqueue and dequeue operations.

1) _____ may resize the queue.

- ○ Only the enqueue operation
- ○ Only the dequeue operation
- ○ Both the enqueue and dequeue operations

2) `(frontIndex + length) % allocationSize` yields the index _____.

- ○ of the item to remove during a dequeue operation

- at which to insert a new item during an enqueue operation
- of the queue's back item

3) ArrayQueueEnqueue() returns false if _____.

- the item is successfully enqueued
- the resize operation fails
- the queue is full

4) An alternate implementation could store the queue's back item index instead of the length.

- True
- False

Worst-case time complexity

Using the implementation from above, worst-case time complexities are the same whether the queue is bounded or unbounded: O(N) for enqueue and O(1) for dequeue.

An alternate implementation of the bounded queue, not presented in this section, uses `maxLength` *as the array's initial allocation size. Such an implementation never needs to resize and so the enqueue operation's worst-case time is O(1).*

5.22 Deque abstract data type (ADT)

This section has been set as optional by your instructor.

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 5.22.1: 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 5.22.2: Deque ADT.

Determine the deque contents after the following operations.

If unable to drag and drop, refresh the page.

push-front 97, push-back 71, pop-front, push-front 45, push-back 68	45, 97, 68
push-back 45, push-back 71, push-front 97, push-front 68, pop-back	45, 71, 68
push-front 71, push-front 68, push-front 97, pop-back, push-front 45	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 deque and determining the length. A ***peek*** operation returns an item in the deque without removing the item.

Table 5.22.1: 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 5.22.3: Common deque 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 5.22.1: Deque ADT.

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Start

Given an empty deque numDeque, what are the deque's contents after the following operation

PushFront(numDeque, 49)
PushBack(numDeque, 70)
PushBack(numDeque, 58)
PushFront(numDeque, 65)

Ex: 1, 2, 3 (commas between values)

After the above operations, what does PeekFront(numDeque) return?

Ex: 5

After the above operations, what does PeekBack(numDeque) return?

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

1 2 3

Check Next

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