Lists, Stacks, and Queues

Computer Science E-22
Harvard Extension School

David G. Sullivan, Ph.D.

Representing a Sequence: Arrays vs. Linked Lists

- Sequence – an ordered collection of items (position matters)
  - we will look at several types: lists, stacks, and queues
- Can represent any sequence using an array *or* a linked list

	array	***linked list***
representation in memory	elements occupy consecutive memory locations	nodes can be at arbitrary locations in memory; the links connect the nodes together
advantages		
disadvantages		

A List as an Abstract Data Type

- list = a sequence of items that supports at least the following functionality:
  - accessing an item at an arbitrary position in the sequence
  - adding an item at an arbitrary position
  - removing an item at an arbitrary position
  - determining the number of items in the list (the list's *length*)
- ADT: specifies *what* a list will do, without specifying the implementation

Review: Specifying an ADT Using an Interface

- Recall that in Java, we can use an interface to specify an ADT:

```
public interface List {
    Object getItem(int i);
    boolean addItem(Object item, int i);
    int length();
    …
}
```

- We make any implementation of the ADT a class that implements the interface:

```
public class MyList implements List {
    ...
```

- This approach allows us to write code that will work with different implementations of the ADT:

```
public static void processList(List l) {
    for (int i = 0; i < l.length(); i++) {
        Object item = l.getItem(i);
        …
```

Our List Interface

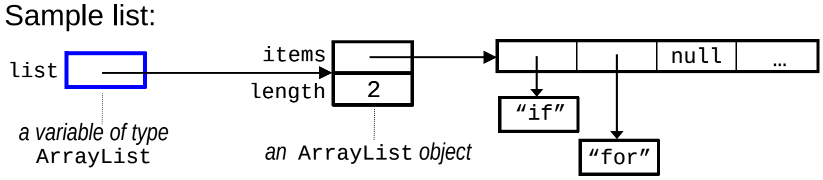
```
public interface List {
    Object getItem(int i);
    boolean addItem(Object item, int i);
    Object removeItem(int i);
    int length();
    boolean isFull();
}
```

- We include an `isFull()` method to test if the list already has the maximum number of items
- Recall that all methods in an interface are assumed to be public.
- The actual interface definition includes comments that describe what each method should do.

Implementing a List Using an Array

```
public class ArrayList implements List {
    private Object[] items;
    private int length;
    public ArrayList(int maxSize) {
        items = new Object[maxSize];
        length = 0;
    }
    public int length() {
        return length;
    }
    public boolean isFull() {
        return (length == items.length);
    }
    ...
}
```

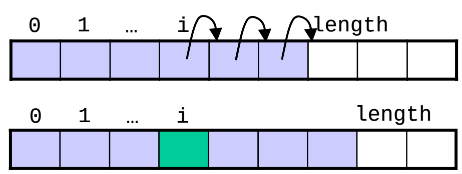
- Sample list:



Adding an Item to an `ArrayList`

- Adding at position i (shifting items i, i+1, … to the right by one):

```
public boolean addItem(Object item, int i) {
    if (i < 0 || i > length)
        throw new IndexOutOfBoundsException();
    if (isFull())
        return false;

    // make room for the new item
    for (int j = length – 1; j >= i; j--)
        items[j + 1] = items[j];

    items[i] = item;
    length++;
    return true;
}
```



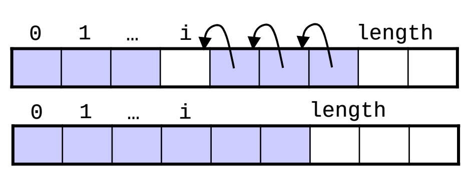
Other `ArrayList` Methods

- Getting item i:

```
public Object getItem(int i) {
    if (i < 0 || i >= length)
        throw new IndexOutOfBoundsException();
    return items[i];
}
```

- Removing item i (shifting items i+1, i+2, … to the left by one):

```
public Object removeItem(int i) {
    if (i < 0 || i >= length)
        throw new IndexOutOfBoundsException();






}
```



Converting an `ArrayList` to a String

- The `toString()` method is designed to allow objects to be displayed in a human-readable format.
- This method is called implicitly when you attempt to print an object or when you perform string concatenation:

```
ArrayList l = new ArrayList();
System.out.println(l);
String str = “My list: ” + l;
System.out.println(str);
```

- A default version of this method is inherited from the `Object` class.
  - returns a `String` consisting of the type of the object and a hash code for the object.
- It usually makes sense to override the default version.

`toString()` Method for the `ArrayList` Class

```
public String toString() {
    String str = "{";

    if (length > 0) {
        for (int i = 0; i < length - 1; i++)
            str = str + items[i] + ", ";
        str = str + items[length – 1];
    }

    str = str + "}"

    return str;
}
```

- Produces a string of the following form:

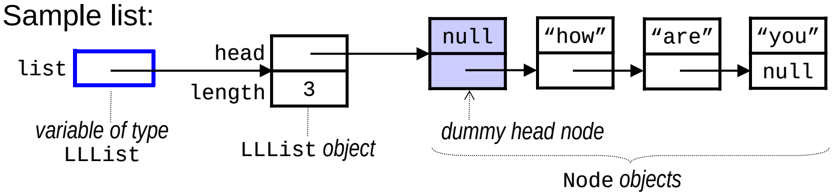
```
{items[0], items[1], … }
```

- Why is the last item added outside the loop?
- Why do we need the `if` statement?

Implementing a List Using a Linked List

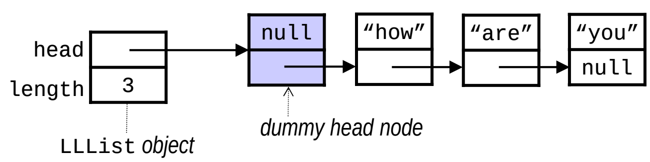
```
public class LLList implements List {
    private Node head;     // dummy head node
    private int length;
    …
}
```

- Sample list:

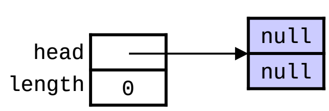


- Differences from the linked list we used for strings:
  - we "embed" the linked list inside another class
    - users of our `LLList` class will never actually touch the nodes
    - users of our `StringNode` class hold a reference to the first node
  - we use a dummy head node
  - we use instance methods instead of static methods
    - `myList.length()` instead of `length(myList)`

Using a Dummy Head Node



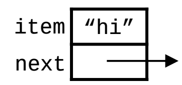
- The dummy head node is always at the front of the linked list.
  - like the other nodes in the linked list, it's of type `Node`
  - it does *not* store an item
  - it does *not* count towards the length of the list
- An empty `LLList` still has a dummy head node:



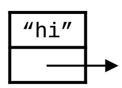
- Using a dummy head node allows us to avoid special cases when adding and removing nodes from the linked list.

An Inner Node Class

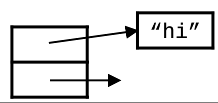
```
public class LLList implements List {
    private class Node {
        private Object item;
        private Node next;

        private Node(Object i, Node n) {
            item = i;
            next = n;
        }
    }
    ...
}
```



- We make `Node` an *inner class*, defining it within `LLList`.
  - allows the `LLList` methods to directly access `Node`’s private members, while restricting all other access
  - the compiler creates this class file: `LLList$Node.class`
- For simplicity, our diagrams show the items inside the nodes.



instead of



Other Details of Our `LLList` Class

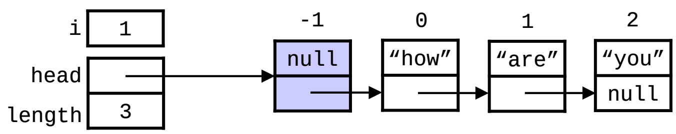
```
public class LLList implements List {
    private class Node {
        ...
    }

    private Node head;
    private int length;

    public LLList() {
        head = new Node(null, null);
        length = 0;
    }

    public boolean isFull() {
        return false;
    }
}
```

- Unlike `ArrayList`, there’s no need to preallocate space for the items. The constructor simply creates the dummy head node.
- The linked list can grow indefinitely, so the list is never full!

Getting a Node

- Private helper method for getting node `i`
  - to get the dummy head node, use `i = -1`

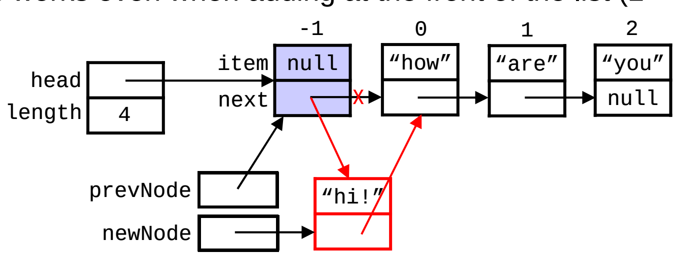
```
private Node getNode(int i) {
    // private method, so we assume i is valid!

    Node trav = __________;
    int travIndex = -1;
    while ( _________________ ) {
        travIndex++;
        _________________________;
    }
    return trav;
}
```



Adding an Item to an `LLList`

```
public boolean addItem(Object item, int i) {
    if (i < 0 || i > length)
        throw new IndexOutOfBoundsException();
    Node newNode = new Node(item, null);
    Node prevNode = getNode(i – 1);
    newNode.next = prevNode.next;
    prevNode.next = newNode;
    length++;
    return true;
}
```

- This works even when adding at the front of the list (`i == 0`):



`addItem()` Without a Dummy Head Node

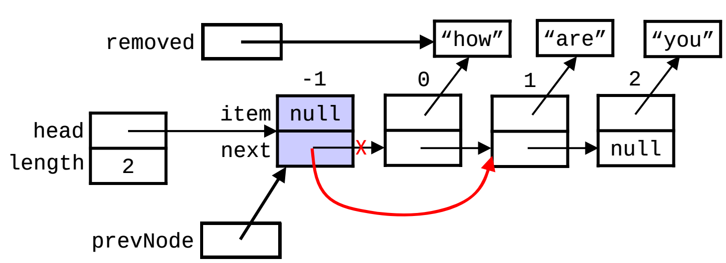
```
public boolean addItem(Object item, int i) {
    if (i < 0 || i > length)
        throw new IndexOutOfBoundsException();

    Node newNode = new Node(item, null);

    if (i == 0) {                   // case 1: add to front
        newNode.next = first;
        first = newNode;
    } else {                        // case 2: i > 0
        Node prevNode = getNode(i – 1);
        newNode.next = prevNode.next;
        prevNode.next = newNode;
    }

    length++;
    return true;
}
```

(instead of a reference named `head` *to the dummy head node, this implementation maintains a reference named* `first` *to the first node, which does hold an item).*

Removing an Item from an `LLList`

```
public Object removeItem(int i) {
    if (i < 0 || i >= length)
        throw new IndexOutOfBoundsException();
    Node prevNode = getNode(i – 1);
    Object removed = prevNode.next.item;
    ___________________________    // what line goes here?
    length--;
    return removed;
}
```

- This works even when removing the first item (`i == 0`):



`toString()` Method for the `LLList` Class

```
public String toString() {
    String str = "{";

    // what should go here?










    str = str + " }"

    return str;
}
```

Counting the Number of Occurrences of an Item

- One possible approach:

```
public class MyClass {
    public static int numOccur(List l, Object item) {
        int numOccur = 0;
        for (int i = 0; i < l.length(); i++) {
            Object itemAt = l.getItem(i);
            if (itemAt.equals(item))
                numOccur++;
        }
        return numOccur;
    } …
```

- Problem: for `LLList` objects, each call to `getItem()` starts at the head of the list and traverses to item `i`.
  - to access item 0, access 1 node
  - to access item 1, access 2 nodes
  - to access item i, access i+1 nodes
  - if length = n, total nodes accessed = 1 + 2 + … + n = $O(n^2)$

Solution 1: Make `numOccur()` an `LLList` Method

```
public class LLList {
    public int numOccur(Object item) {
        int numOccur = 0;
        Node trav = head.next;  // skip the dummy head node
        while (trav != null) {
            if (trav.item.equals(item))
                numOccur++;
            trav = trav.next;
        }
        return numOccur;
    } …
```

- Each node is only visited once, so the # of accesses = n = O(n)
- Problem: we can't anticipate all of the types of operations that users may wish to perform.
- We would like to give users the general ability to iterate over the list.

Solution 2: Give Access to the Internals of the List

- Make our private helper method `getNode()` a public method.
- Make `Node` a non-inner class and provide getter methods.
- This would allow us to do the following:

```
public class MyClass {
    public static int numOccur(LLList l, Object item) {
        int numOccur = 0;
        Node trav = l.getNode(0);
        while (trav != null) {
            Object itemAt = trav.getItem();
            if (itemAt.equals(item))
                numOccur++;
            trav = trav.getNext();
        }
        return numOccur;
    } …
}
```

- What's wrong with this approach?

Solution 3: Provide an Iterator

- An iterator is an object that provides the ability to iterate over a list *without* violating encapsulation.
- Our iterator class will implement the following interface:

```
public interface ListIterator {
    // Are there more items to visit?
    boolean hasNext();

    // Return next item and advance the iterator.
    Object next();
}
```

- The iterator starts out prepared to visit the first item in the list, and we use `next()` to access the items sequentially.
- Ex: position of the iterator is shown by the cursor symbol (|)

after the iterator `i` *is created:*	| "do" "we" "go" …
after calling `i.next()`, *which returns* "do":	"do" | "we" "go" …
after calling `i.next()`, *which returns* "we":	"do" "we" | "go" …

`numOccur()` Using an Iterator

```
public class MyClass {
    public static int numOccur(List l, Object item) {
        int numOccur = 0;
        ListIterator iter = l.iterator();
        while (iter.hasNext()) {
            Object itemAt = iter.next();
            if (itemAt.equals(item))
                numOccur++;
        }
        return numOccur;
    } …
}
```

- The `iterator()` method returns an iterator object that is ready to visit the first item in the list. (Note: we also need to add the header of this method to the `List` interface.)
- Note that `next()` does two things at once:
  - gets an item
  - advances the iterator.

Using an Inner Class for the Iterator

```
public class LLList {
    public ListIterator iterator() {
        return new LLListIterator();
    }

    private class LLListIterator implements ListIterator {
        private Node nextNode;
        private Node lastVisitedNode;

        public LLListIterator() {
            …
    }
}
```

- Using a inner class gives the iterator access to the list's internals.
- Because `LLListIterator` is a private inner class, methods outside `LLList` can't create `LLListIterator` objects or have variables that are declared to be of type `LLListIterator`.
- Other classes use the *interface name* as the declared type, e.g.:
  `ListIterator iter = l.iterator();`

`LLListIterator` Implementation

```
private class LLListIterator implements ListIterator {
    private Node nextNode;
    private Node lastVisitedNode;

    public LLListIterator() {
        nextNode = head.next;    // skip over head node
        lastVisitedNode = null;
    }
    …
}
```

- Two instance variables:
  - `nextNode` keeps track of the next node to visit
  - `lastVisitedNode` keeps track of the most recently visited node
    - not needed by `hasNext()` and `next()`
    - what iterator operations might we want to add that *would* need this reference?

`LLListIterator` Implementation (cont.)

```
private class LLListIterator implements ListIterator {
    private Node nextNode;
    private Node lastVisitedNode;

    public LLListIterator() {
        nextNode = head.next;    // skip over dummy node
        lastVisitedNode = null;
    }

    public boolean hasNext() {
         return (nextNode != null);
    }

    public Object next() {
        if (nextNode == null)
            throw new NoSuchElementException();

        Object item = nextNode.item;
        lastVisited = nextNode;
        nextNode = nextNode.next;

        return item;
    }
}
```

More About Iterators

- In theory, we could write list-iterator methods that were methods of the list class itself.
- Instead, our list-iterator methods are encapsulated within an iterator object.
  - allows us to have multiple iterations active at the same time:

```
ListIterator i = l.iterator();
while (i.hasNext()) {
    ListIterator j = l.iterator();
    while (j.hasNext()) {
        …
```

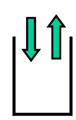
- Java's built-in *collection classes* all provide iterators.
  - `LinkedList`, `ArrayList`, etc.
  - the built-in `Iterator` interface specifies the iterator methods
    - they include `hasNext()` and `next()` methods like ours

Efficiency of the List Implementations

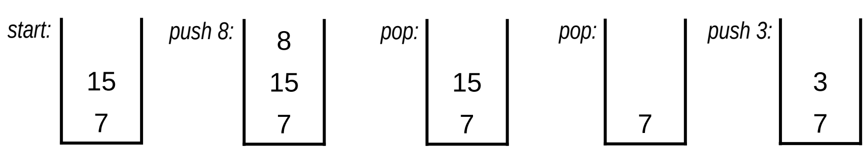
n = number of items in the list

	`ArrayList`	`LLList`
`getItem()`		
`addItem()`		
`removeItem()`		
space efficiency		

Stack ADT



- A stack is a sequence in which:
  - items can be added and removed only at one end (the *top*)
  - you can only access the item that is currently at the top
- Operations:
  - push: add an item to the top of the stack
  - pop: remove the item at the top of the stack
  - peek: get the item at the top of the stack, but don't remove it
  - isEmpty: test if the stack is empty
  - isFull: test if the stack is full
- Example: a stack of integers



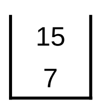
A Stack Interface: First Version

```
public interface Stack {
    boolean push(Object item);
    Object pop();
    Object peek();
    boolean isEmpty();
    boolean isFull();
}
```

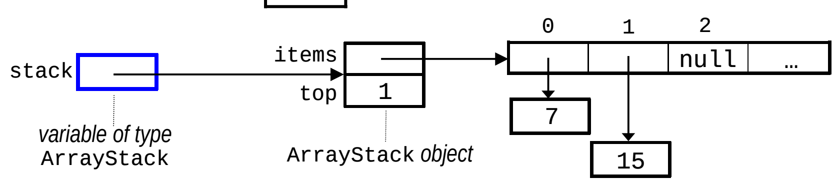
- `push()` returns `false` if the stack is full, and `true` otherwise.
- `pop()` and `peek()` take no arguments, because we know that we always access the item at the top of the stack.
  - return `null` if the stack is empty.
- The interface provides no way to access/insert/delete an item at an arbitrary position.
  - encapsulation allows us to ensure that our stacks are manipulated only in ways that are consistent with what it means to be stack

Implementing a Stack Using an Array: First Version

```
public class ArrayStack implements Stack {
    private Object[] items;
    private int top;    // index of the top item

    public ArrayStack(int maxSize) {
        items = new Object[maxSize];
        top = -1;
    }
    ...
}
```

- Example: the stack 

would be represented as follows:



- Items are added from left to right. The instance variable `top` stores the index of the item at the top of the stack.

Limiting a Stack to Objects of a Given Type

- We can do this by using a *generic* interface and class.
- Here is a generic version of our `Stack` interface:

```
public interface Stack<T> {
    boolean push(T item);
    T pop();
    T peek();
    boolean isEmpty();
    boolean isFull();
}
```

- It includes a *type variable* `T` in its header and body.
- This type variable is used as a placeholder for the actual type of the items on the stack.

A Generic `ArrayStack` Class

```
public class ArrayStack<T> implements Stack<T> {
    private T[] items;
    private int top;    // index of the top item
    …
    public boolean push(T object) {
        …
    }
    …
}
```

- Once again, a type variable `T` is used as a placeholder for the actual type of the items.
- When we create an `ArrayStack`, we specify the type of items that we intend to store in the stack:

```
ArrayStack<Integer> s1 = new ArrayStack<Integer>(10);
ArrayStack<String> s2 = new ArrayStack<String>(5);
ArrayStack<Object> s3 = new ArrayStack<Object>(20);
```

`ArrayStack` Constructor

- Java doesn't allow you to create an object or array using a type variable. Thus, we *cannot* do this:

```
public ArrayStack(int maxSize) {
    items = new T[maxSize];   // not allowed
    top = -1;
}
```

- To get around this limitation, we create an array of type `Object` and cast it to be an array of type `T`:

```
public ArrayStack(int maxSize) {
    items = (T[])new Object[maxSize];
    top = -1;
}
```

(This doesn't produce a `ClassCastException` at runtime, because in the compiled version of the class, `T` is replaced with `Object`.)

- The cast generates a compile-time warning, but we'll ignore it.
- Java's built-in `ArrayList` class takes this same approach.

More on Generics

- When a collection class uses the type `Object` for its items, we often need to use casting:

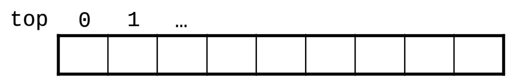
```
LLList list = new LLList();
list.addItem("hello");
list.addItem("world");
String item = (String)list.getItem(0);
```

- Using generics allows us to avoid this:

```
ArrayStack<String> s = new ArrayStack<String>;
s.push("hello");
s.push("world");
String item = s.pop();    // no casting needed
```

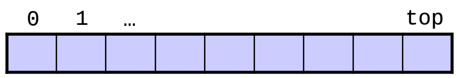
Testing if an `ArrayStack` is Empty or Full

- Empty stack:




```
public boolean isEmpty() {
    return (top == -1);
}
```

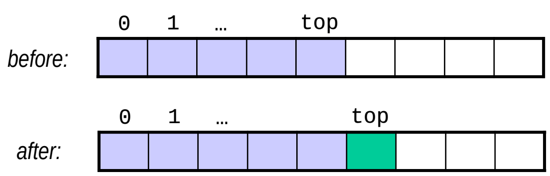
- Full stack:




```
public boolean isFull() {
    return (top == items.length - 1);
}
```

Pushing an Item onto an `ArrayStack`

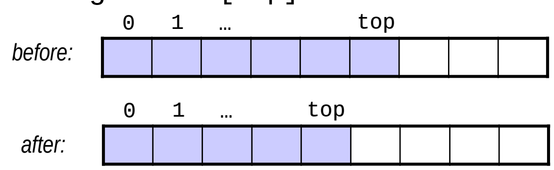
- We increment `top` before adding the item:




```
public boolean push(T item) {
    if (isFull())
        return false;
    top++;
    items[top] = item;
    return true;
}
```

`ArrayStack pop() and peek()`

- pop: need to get `items[top]` *before* we decrement `top`.




```
public T pop() {
    if (isEmpty())
        return null;
    T removed = items[top];
    items[top] = null;
    top--;
    return removed;
}
```

- peek just returns `items[top]` without decrementing `top`.

`toString()` Method for the `ArrayStack` Class

- Assume that we want the method to show us everything in the stack – returning a string of the form

  `"{top, one-below-top, two-below-top, … bottom}"`

```
public String toString() {
    String str = "{";

    // what should go here?





    str = str + "}"

    return str;
}
```

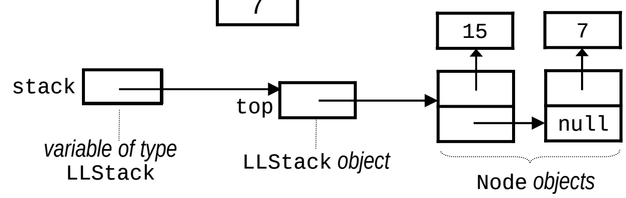
Implementing a Generic Stack Using a Linked List

```
public class LLStack<T> implements Stack<T> {
    private Node top;    // top of the stack
    …
}
```

- Example: the stack

15
7

would be represented as follows:



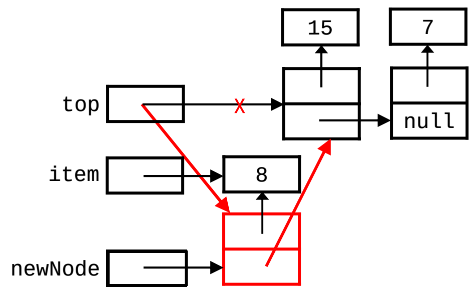
- Things worth noting:
  - our `LLStack` class needs only a single instance variable—a reference to the first node, which holds the top item
  - top item = leftmost item (vs. rightmost item in `ArrayStack`)
  - we don't need a dummy node, because we always insert at the front, and thus the insertion code is already simple

Other Details of Our `LLStack` Class

```
public class LLStack<T> implements Stack<T> {
    private class Node {
        private T item;
        private Node next;
        ...
    }

    private Node top;

    public LLStack() {
        top = null;
    }
    public boolean isEmpty() {
        return (top == null);
    }
    public boolean isFull() {
        return false;
    }
}
```

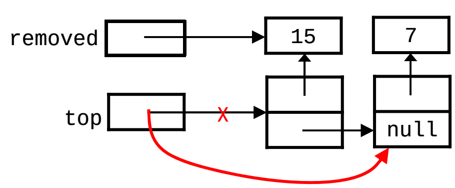
- The inner `Node` class uses the type parameter `T` for the item.
- We don't need to preallocate any memory for the items.
- The stack is never full!

LLStack.push




```
public boolean push(T item) {


}
```

LLStack pop() and peek()




```
public T pop() {
    if (isEmpty())
        return null;
    T removed = __________________;


}

public T peek() {
    if (isEmpty())
        return null;
    return top.item;
}
```

`toString()` Method for the `LLStack` Class

- Again, assume that we want a string of the form

```
"{top, one-below-top, two-below-top, … bottom}"
```

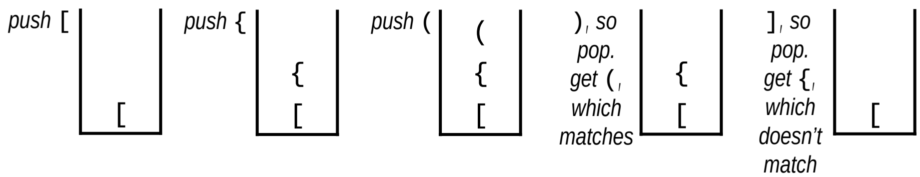
```
public String toString() {
    String str = "{";

    // what should go here?





    str = str + "}"

    return str;
}
```

Efficiency of the Stack Implementations

	`ArrayStack`	**`LLStack`**
`push()`	*O*(1)	*O*(1)
`pop()`	*O*(1)	*O*(1)
`peek()`	*O*(1)	*O*(1)
space efficiency	*O*(m) where m is the *anticipated* maximum number of items	*O*(n) where n is the number of items currently on the stack

Applications of Stacks

- The runtime stack in memory
- Converting a recursive algorithm to an iterative one by using a stack to emulate the runtime stack
- Making sure that delimiters (parens, brackets, etc.) are balanced:
  - push open (i.e., left) delimiters onto a stack
  - when you encounter a close (i.e., right) delimiter, pop an item off the stack and see if it matches
  - example: `5 * [3 + {(5 + 16 – 2)]`



- Evaluating arithmetic expressions (see textbooks)

An Example of Switching Between Implementations

- In the example code for this unit, there is a test program for each type of sequence:

  `ListTester.java`, `StackTester.java`, `QueueTester.java`

- Each test program uses a variable that has the appropriate *interface* as its type. For example:

```
Stack<String> myStack;
```

- The program asks you which implementation you want to test, and it calls the corresponding constructor:

```
if (type == 1)
    myStack = new ArrayStack<String>(10);
else if (type == 2)
    myStack = new LLStack<String>();
```

- This is an example of what principle of object-oriented programming?

Declared Type vs. Actual Type

- An object has two types that may or may not be the same.
  - declared type: type specified when declaring the variable
  - actual type: type specified when creating the object
- Consider again our `StackTester` program:

```
int type;
Stack<String> myStack;
Scanner in = new Scanner(System.in);
...
type = in.nextInt();
if (type == 1)
    myStack = new ArrayStack<String>(10);
else if (type == 2)
    myStack = new LLStack<String>();
```

- What is the declared type of `myStack`?
- What is its actual type?

Dynamic Binding

- Example of how `StackTester` tests the methods:

```
String item = myStack.pop();
```

- There are two different versions of the `pop` method, but we don't need two different sets of code to test them.
  - the line shown above will test whichever version of the method the user has specified!
- At runtime, the Java interpreter selects the version of the method that is appropriate to the *actual* type of `myStack`.
  - This is known as *dynamic binding.*
  - Why can't this selection be done by the compiler?

Determining if a Method Call is Valid

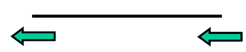
- The compiler uses the *declared* type of an object to determine if a method call is valid.
- Example:
  - assume that we add our `iterator()` method to `LLList` but do not add a header for it to the `List` interface
  - under that scenario, the following will *not* work:

```
List myList = new LLList();
ListIterator iter = myList.iterator();
```

- Because the declared type of `myList` is `List`, the compiler looks for that method in `List`.
  - if it's not there, the compiler will not compile the code.
- We can use a type cast to reassure the compiler:

```
ListIterator iter = ((LLList)myList).iterator();
```

Queue ADT



- A queue is a sequence in which:
  - items are added at the rear and removed from the front
    - first in, first out (FIFO) (vs. a stack, which is last in, first out)
  - you can only access the item that is currently at the front
- Operations:
  - insert: add an item at the rear of the queue
  - remove: remove the item at the front of the queue
  - peek: get the item at the front of the queue, but don't remove it
  - isEmpty: test if the queue is empty
  - isFull: test if the queue is full
- Example: a queue of integers

start: `12 8`
insert 5: `12 8 5`
remove: `8 5`

Our Generic Queue Interface

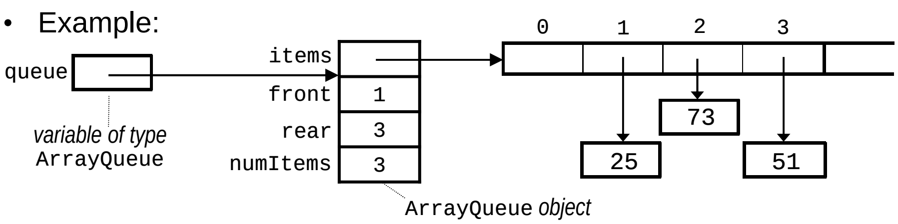
```
public interface Queue<T> {
    boolean insert(T item);
    T remove();
    T peek();
    boolean isEmpty();
    boolean isFull();
}
```

- `insert()` returns `false` if the queue is full, and `true` otherwise.
- `remove()` and `peek()` take no arguments, because we know that we always access the item at the front of the queue.
  - return `null` if the queue is empty.
- Here again, we will use encapsulation to ensure that the data structure is manipulated only in valid ways.

Implementing a Queue Using an Array

```
public class ArrayQueue<T> implements Queue<T> {
    private T[] items;
    private int front;
    private int rear;
    private int numItems;
    ...
}
```

- Example:



- We maintain two indices:
  - `front`: the index of the item at the front of the queue
  - `rear`: the index of the item at the rear of the queue

Avoiding the Need to Shift Items

- Problem: what do we do when we reach the end of the array?

  example: a queue of integers:

front					rear		
54	4	21	17	89	65		

  the same queue after removing two items and inserting one:

		front				rear	
		21	17	89	65	43	

  to insert two or more additional items, would need to shift items left

- Solution: maintain a *circular queue*. When we reach the end of the array, we wrap around to the beginning.

  the same queue after inserting two additional items:

rear		front					
5		21	17	89	65	43	81

A Circular Queue

- To get the front and rear indices to wrap around, we use the modulus operator (%).
- `x % y` = the remainder produced when you divide `x` by `y`
  - examples:
    - `10 % 7 = 3`
    - `36 % 5 = 1`
- Whenever we increment `front` or `rear`, we do so modulo the length of the array.

```
front = (front + 1) % items.length;
rear = (rear + 1) % items.length;
```

- Example:

		front					rear
		21	17	89	65	43	81

`items.length = 8, rear = 7`

before inserting the next item: `rear = (7 + 1) % 8 = 0`

which wraps `rear` around to the start of the array

Testing if an `ArrayQueue` is Empty

- Initial configuration:

  `rear = -1`
  `front = 0`

rear	front						

- We increment `rear` on every insertion, and we increment `front` on every removal.

  after one insertion:

rear front						
15						

  after two insertions:

front	rear					
15	32					

  after one removal:

	front rear					
	32					

  after two removals:

	rear	front				

- The queue is empty when `rear` is one position "behind" `front`:

  `((rear + 1) % items.length) == front`

Testing if an `ArrayQueue` is Full

- Problem: if we use all of the positions in the array, our test for an empty queue will also hold when the queue is full!

  example: what if we added one more item to this queue?

rear		front				
5		21	17	89	65	43	81

- This is why we maintain `numItems`!

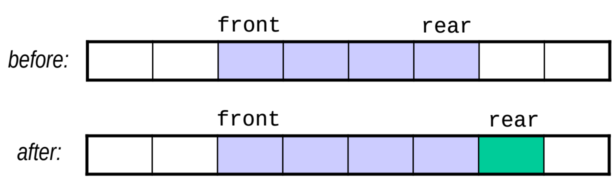
```
public boolean isEmpty() {
    return (numItems == 0);
}

public boolean isFull() {
    return (numItems == items.length);
}
```

Constructor

```
public ArrayQueue(int maxSize) {
    items = (T[])new Object[maxSize];
    front = 0;
    rear = -1;
    numItems = 0;
}
```

Inserting an Item in an `ArrayQueue`

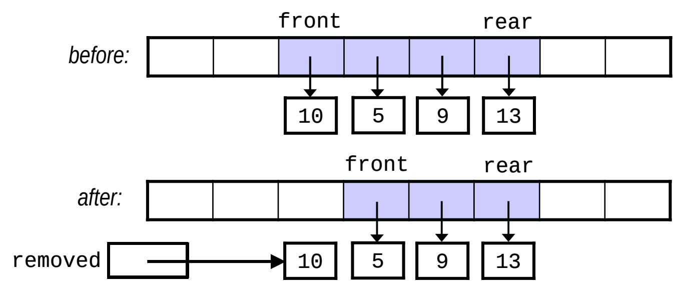
- We increment `rear` before adding the item:




```
public boolean insert(T item) {
    if (isFull())
        return false;
    rear = (rear + 1) % items.length;
    items[rear] = item;
    numItems++;
    return true;
}
```

ArrayQueue remove()

- remove: need to get `items[front]` *before* we increment `front`.

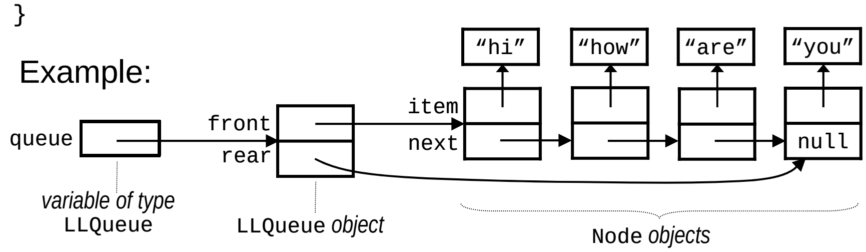



```
public T remove() {
    if (isEmpty())
        return null;
    T removed = items[front];
    items[front] = null;
    front = (front + 1) % items.length;
    numItems--;
    return removed;
}
```

Implementing a Queue Using a Linked List

```
public class LLQueue<T> implements Queue<T> {
    private Node front;    // front of the queue
    private Node rear;     // rear of the queue
    …
}
```

- Example:



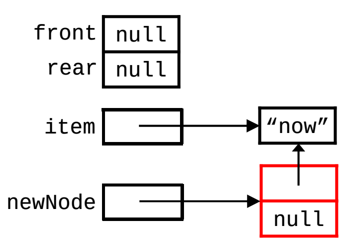
- Because a linked list can be easily modified on both ends, we don't need to take special measures to avoid shifting items, as we did in our array-based implementation.

Other Details of Our `LLQueue` Class

```
public class LLQueue<T> implements Queue<T> {
    private class Node {
        private T item;
        private Node next;
        ...
    }

    private Node front;
    private Node rear;

    public LLQueue() {
        front = rear = null;
    }
    public boolean isEmpty() {
        return (front == null);
    }
    public boolean isFull() {
        return false;
    }
    …
}
```

- Much simpler than the array-based queue!

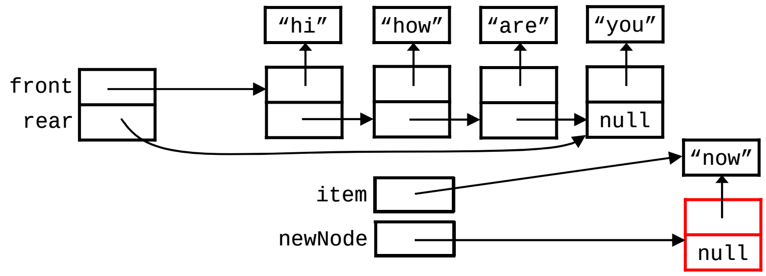
Inserting an Item in an Empty `LLQueue`



The `next` field in the `newNode` will be `null` in either case. Why?

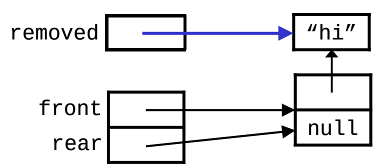
```
public boolean insert(T item) {
    Node newNode = new Node(item, null);

    if (isEmpty())

    else {


    }

    return true;
}
```

Inserting an Item in a Non-Empty `LLQueue`



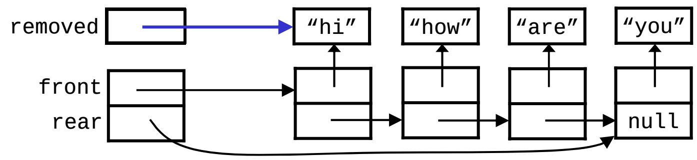

```
public boolean insert(T item) {
    Node newNode = new Node(item, null);

    if (isEmpty())

    else {


    }

    return true;
}
```

Removing from an `LLQueue` with One Item




```
public T remove() {
    if (isEmpty())
        return null;

    T removed = ______________;
    if (front == rear)      // removing the only item

    else


    return removed;
}
```

Removing from an `LLQueue` with Two or More Items




```
public T remove() {
    if (isEmpty())
        return null;

    T removed = ______________;
    if (front == rear)       // removing the only item

    else


    return removed;
}
```

Efficiency of the Queue Implementations

	`ArrayQueue`	`LLQueue`
`insert()`	*O*(1)	*O*(1)
`remove()`	*O*(1)	*O*(1)
`peek()`	*O*(1)	*O*(1)
space efficiency	*O*(m) where m is the *anticipated* maximum number of items	*O*(n) where n is the number of items currently in the queue

Applications of Queues

- first-in first-out (FIFO) inventory control
- OS scheduling: processes, print jobs, packets, etc.
- simulations of banks, supermarkets, airports, etc.
- breadth-first traversal of a graph or level-order traversal of a binary tree (more on these later)

Lists, Stacks, and Queues in Java's Class Library

- Lists:
  - interface: `java.util.List<T>`
    - slightly different methods, some extra ones
  - array-based implementations: `java.util.ArrayList<T>`
    `java.util.Vector<T>`
    - the array is expanded as needed
    - `Vector` has extra non-`List` methods
  - linked-list implementation: `java.util.LinkedList<T>`
    - `addLast()` provides *O*(1) insertion at the end of the list
- Stacks: `java.util.Stack<T>`
    - extends `Vector` with methods that treat a vector like a stack
    - problem: other `Vector` methods can access items below the top
- Queues:
  - interface: `java.util.Queue<T>`
  - implementation: `java.util.LinkedList<T>.`