Unit 8, Part 2

Lists, Stacks, and Queues

Computer Science S-111
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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	• provide random access (access to any item in constant time) • no extra memory needed for links	• can grow to an arbitrary length • allocate nodes as needed • inserting or deleting does *not* require shifting items
disadvantages	• have to preallocate the memory needed for the maximum sequence size • inserting or deleting can require shifting items	• no random access (may need to traverse the list) • need extra memory for links

The List ADT

- A list is a sequence in which items can be accessed, inserted, and removed *at any position in the sequence*.
- The operations supported by our List ADT:
  - `getItem(i)`: get the item at position i
  - `addItem(item, i)`: add the specified item at position i
  - `removeItem(i)`: remove the item at position i
  - `length()`: get the number of items in the list
  - `isFull()`: test if the list already has the maximum number of items
- Note that we *don't* specify *how* the list will be implemented.

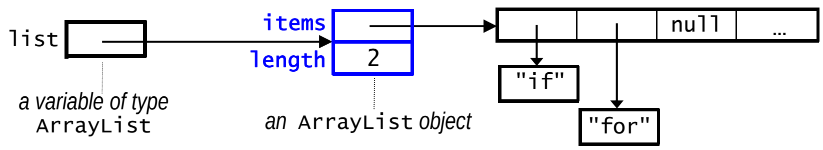
Our List Interface

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

- Recall that all methods in an interface *must* be public , so we don't need the keyword `public` in the headers.
- We use the `Object` type to allow for items of any type.
- `addItem()` returns `false` if the list is full, and `true` otherwise.

Implementing a List Using an Array

```
public class ArrayList implements List {
    private Object[] items;
    private int length;

    public ArrayList(int maxSize) {
        // code to check for invalid maxSize goes here...
        this.items = new Object[maxSize];
        this.length = 0;
    }

    public int length() {
        return this.length;
    }

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



Recall: The Implicit Parameter

```
public class ArrayList implements List {
    private Object[] items;
    private int length;

    public ArrayList(int maxSize) {
        this.items = new Object[maxSize];
        this.length = 0;
    }

    public int length() {
        return this.length;
    }

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

- All non-static methods have an implicit parameter (`this`) that refers to the called object.
- In most cases, we're allowed to omit it!
  - we'll do so in the remaining notes

Omitting The Implicit Parameter

```
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);
    }
    ...
}
```

- In a non-static method, if we use a variable that
  - isn't declared in the method
  - has the name of one of the fields

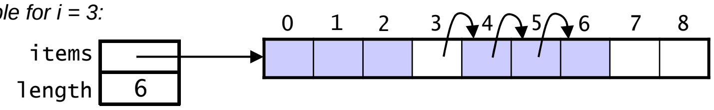
  Java assumes that we're using the field.

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 (item == null || i < 0 || i > length) {
        throw new IllegalArgumentException();
    } else 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;
}
```

example for i = 3:

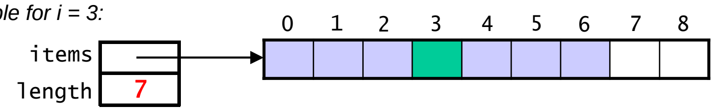


Adding an Item to an `ArrayList`

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

```
public boolean addItem(Object item, int i) {
    if (item == null || i < 0 || i > length) {
        throw new IllegalArgumentException();
    } else 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;
}
```

example for i = 3:

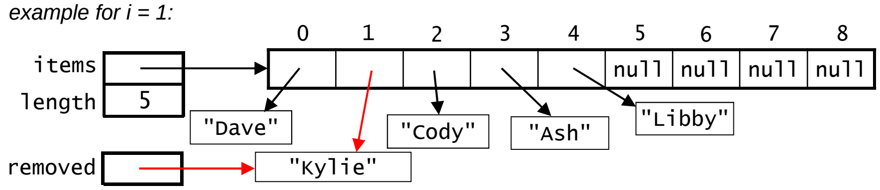


Removing an Item from an `ArrayList`

- 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();
    }
    Object removed = items[i];

    // shift items after items[i] to the left
    for (int j = i; j < length - 1; j++) {
        ____________________________;
    }
    items[length - 1] = null;

    length--;
    return removed;
}
```

example for i = 1:



Getting an Item from an `ArrayList`

- Getting item i (without removing it):

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

`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;
}
```

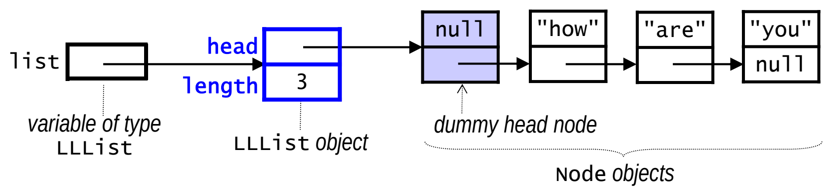
- Produces a string of the following form:

```
{items[0], items[1], … }
```

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

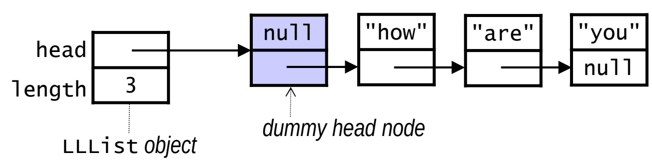
Implementing a List Using a Linked List

```
public class LLList implements List {
    private Node head;
    private int length;
    ...
}
```

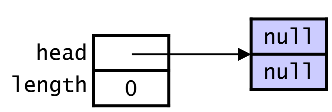


- Differences from the linked lists we used for strings:
  - we "embed" the linked list inside another class
    - users of our `LLList` class won't actually touch the nodes
  - we use non-static methods instead of static ones
    `myList.length()` instead of `length(myList)`
  - we use a special *dummy head node* as the first node

Using a Dummy Head Node



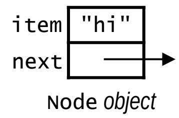
- The dummy head node is always at the front of the linked list.
  - like the other nodes in the linked list, it's of type `Node`
  - it does *not* store an item
  - it does *not* count towards the length of the list
- Using it allows us to avoid special cases when adding and removing nodes from the linked list.
- An empty `LLList` still has a dummy head node:



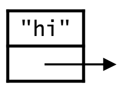
An Inner Class for the Nodes

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

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

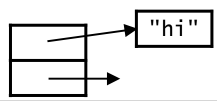
`private` *since only* `LLList` *will use it*



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



instead of



Other Details of Our `LLList` Class

```
public class LLList implements List {
    private class Node {
        // see previous slide
    }

    private Node head;
    private int length;

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

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

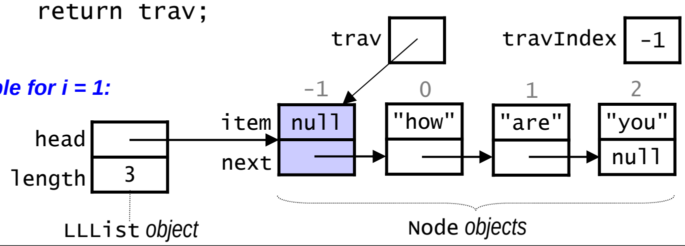
- Unlike `ArrayList`, there's no need to preallocate space for the items. The constructor simply creates the dummy head node.
- The linked list can grow indefinitely, so the list is never full!

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;
}
```

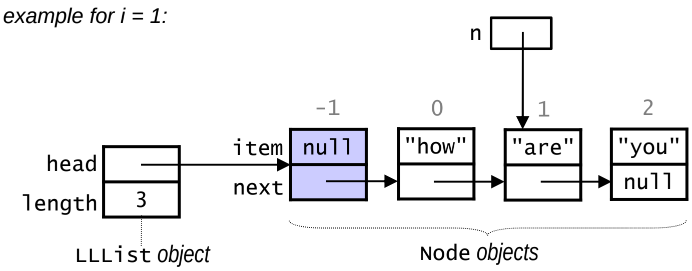
example for i = 1:



Getting an Item

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

    Node n = getNode(i);
    return ________;
}
```

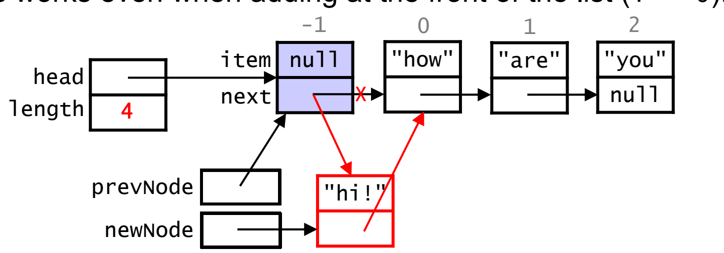
example for i = 1:



Adding an Item to an `LLList`

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

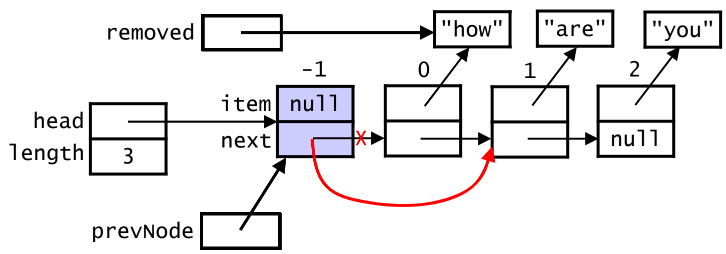
```
public boolean addItem(Object item, int i) {
    if (item == null || i < 0 || i > length) {
        throw new IllegalArgumentException();
    }
    Node newNode = new Node(item, null);

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

    length++;
    return true;
}
```

(the gray code shows what we would need to add if we didn't have a dummy head node)

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;
}
```

Efficiency of the List ADT Implementations

n = number of items in the list

	`ArrayList`	`LLList`
`getItem()`	only one case:	***best:*** ***worst:*** ***average:***
`addItem()`	***best:*** ***worst:*** ***average:***	***best:*** ***worst:*** ***average:***

Efficiency of the List ADT Implementations (cont.)

n = number of items in the list

	`ArrayList`	`LLList`
`removeItem()`	***best:*** ***worst:*** ***average:***	***best:*** ***worst:*** ***average:***
space efficiency		

Counting the Number of Occurrences of an Item

```
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;
    } ...
```

- This method works fine if we pass in an `ArrayList` object.
  - time efficiency (as a function of the length, n) = ?
- However, it's *not* efficient if we pass in an `LLList`.
  - each call to `getItem()` calls `getNode()`
  - to access item 0, `getNode()` accesses 2 nodes (dummy + node 0)
  - to access item 1, `getNode()` accesses 3 nodes
  - to access item i, `getNode()` accesses i+2 nodes
  - 2 + 3 + … + (n+1) = ?

Solution: Provide 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;
    } ...
```

- We add an `iterator()` method to the `List` interface.
  - it returns a separate *iterator object* that can efficiently iterate over the items in the list
- The iterator has two key methods:
  - `hasNext()`: tells us if there are items we haven't seen yet
  - `next()`: returns the next item *and* advances the iterator

An Interface for List Iterators

- Here again, the interface only includes the method headers:

```
public interface ListIterator { // in ListIterator.java
    boolean hasNext();
    Object next();
}
```

- We can then implement this interface for each type of list:
  - `LLListIterator` for an iterator that works with `LLLists`
  - `ArrayListIterator` for an iterator for `ArrayLists`

- We use the interfaces when declaring variables in client code:

```
public class MyClass {
    public static int numOccur(List l, Object item) {
        int numOccur = 0;
        ListIterator iter = l.iterator();
        ...
```

  - doing so allows the code to work for any type of list!

Using an Inner Class for the Iterator

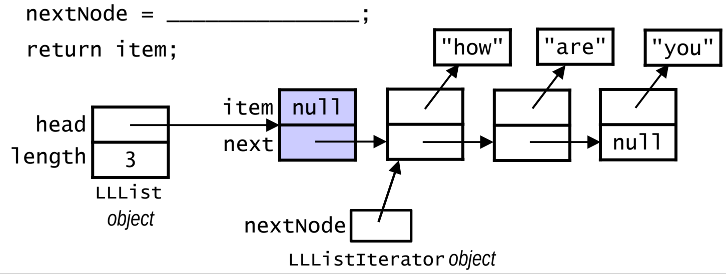
```
public class LLList {
    private Node head;
    private int length;

    private class LLListIterator implements ListIterator {
        private Node nextNode;  // points to node with the next item

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

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

- Using an inner class gives the iterator access to the list's internals.

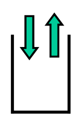
- The `iterator()` method is an `LLList` method.
  - it creates an instance of the inner class and returns it
  - its return type is the interface type
    - so it will work in the context of client code

Full `LLListIterator` Implementation

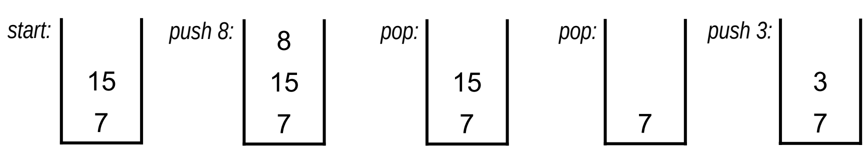
```
private class LLListIterator implements ListIterator {
    private Node nextNode;     // points to node with the next item

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

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

    public Object next() {
        // throw an exception if nextNode is null

        Object item = _______________;

        nextNode = _______________;

        return item;
    }
}
```



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



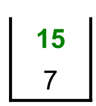
A Stack Interface: First Version

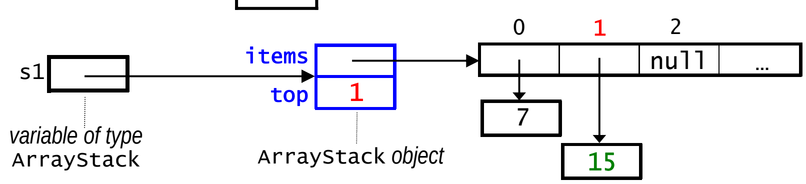
```
public interface Stack {
    boolean push(Object item);
    Object pop();
    Object peek();
    boolean isEmpty();
    boolean isFull();
}
```

- `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 only manipulated in appropriate ways

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) {
        // code to check for invalid maxSize goes here...
        items = new Object[maxSize];
        top = -1;
    }
    ...
```

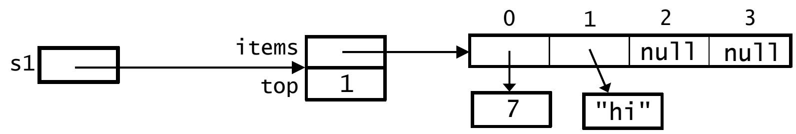
- Example: the stack 



- Items are added from left to right (top item = the rightmost one).
  - `push()` and `pop()` won't require any shifting!

Collection Classes and Data Types

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



- So far, our collections have allowed us to add objects of any type.

```
ArrayStack s1 = new ArrayStack(4);
s1.push(7);    // 7 is turned into an Integer object for 7
s1.push("hi");
String item = s1.pop();           // won't compile
String item = (String)s1.pop();   // need a type cast
```

- We'd like to be able to limit a given collection to one type.

```
ArrayStack<String> s2 = new ArrayStack<String>(10);
s2.push(7);                 // won't compile
s2.push("hello");
String item = s2.pop();    // no cast needed!
```

Limiting a Stack to Objects of a Given Type

- We can do this by using a *generic* interface and class.

- Here's 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.
  - used as a placeholder for the actual type of the items

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 item) {
        …
    }
    …
}
```

- 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<String> s1 = new ArrayStack<String>(10);
ArrayStack<Integer> s2 = new ArrayStack<Integer>(25);
```

- We can still allow for a mixed-type collection:

```
ArrayStack<Object> s3 = new ArrayStack<Object>(20);
```

Using a Generic Class

```
public class ArrayStack<String> {
    private String[] items;
    private int top;
    ...
    public boolean push(String item) {
        ...
```

```
ArrayStack<String> s1 =
  new ArrayStack<String>(10);
```

```
public class ArrayStack<T> ... {
    private T[] items;
    private int top;
    ...
    public boolean push(T item) {
        ...
```

```
ArrayStack<Integer> s2 =
  new ArrayStack<Integer>(25);
```

```
public class ArrayStack<Integer> {
    private Integer[] items;
    private int top;
    ...
    public boolean push(Integer item) {
        ...
```

`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) {
    // code to check for invalid maxSize goes here...
    items = new T[maxSize];    // not allowed
    top = -1;
}
```

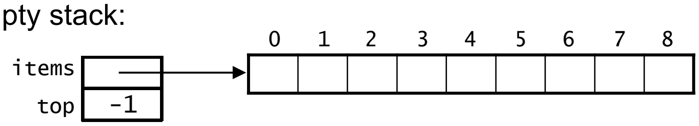
- Instead, we do this:

```
public ArrayStack(int maxSize) {
    // code to check for invalid maxSize goes here...
    items = (T[])new Object[maxSize];
    top = -1;
}
```

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

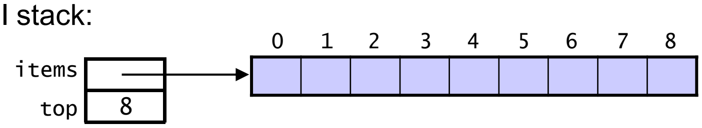
Testing if an `ArrayStack` is Empty or Full

- Empty stack:



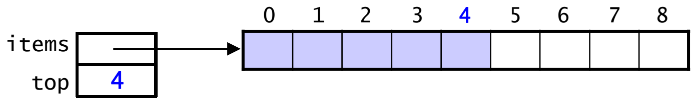

```
public boolean isEmpty() {
    return (top == -1);
}
```

- Full stack:



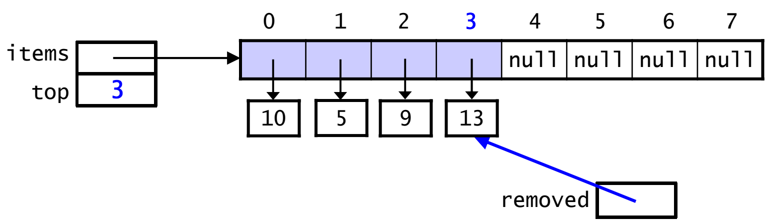

```
public boolean isFull() {
    return (top == items.length - 1);
}
```

Pushing an Item onto an `ArrayStack`




```
public boolean push(T item) {
    // code to check for a null item goes here
    if (isFull()) {
        return false;
    }
    top++;
    items[top] = item;
    return true;
}
```

`ArrayStack pop() and peek()`



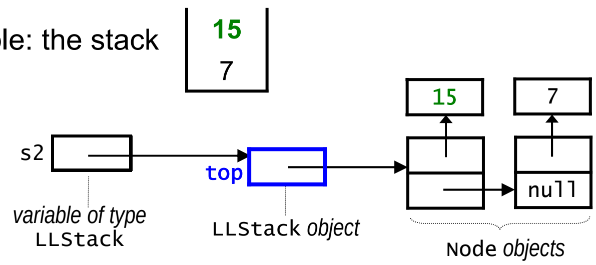

```
public T pop() {
    if (isEmpty()) {
        return null;
    }

    ______ removed = items[top];
    items[top] = null;
    top--;
    return removed;
}
```

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

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



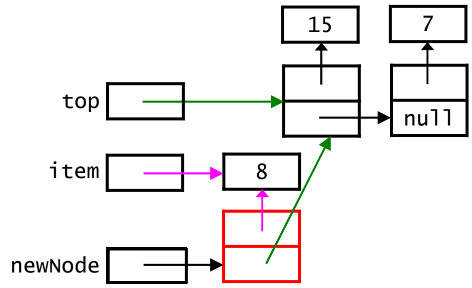
- Things worth noting:
  - our `LLStack` class needs only a single field: a reference to the first node, which holds the top item
  - top item = leftmost item (vs. rightmost item in `ArrayStack`)
  - we don't need a dummy node
    - only one case: always insert/delete at the front of the list!

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;
    }
}
```

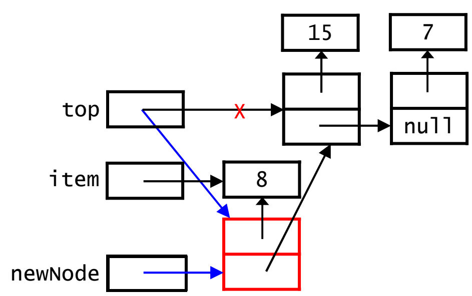
- The inner `Node` class uses the type parameter `T` for the item.
- We don't need to preallocate any memory for the items.
- The stack is never full!

LLStack push()



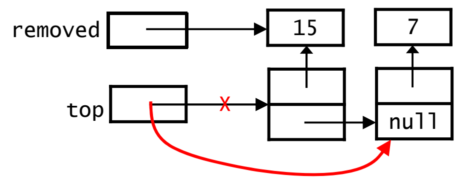

```
public boolean push(T item) {
    // code to check for a null item goes here
    Node newNode = new Node(item, top);
    top = newNode;
    return true;
}
```

LLStack push()




```
public boolean push(T item) {
    // code to check for a null item goes here
    Node newNode = new Node(item, top);
    top = newNode;
    return true;
}
```

LLStack pop() and peek()




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

    _____________________________;
    return removed;
}

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

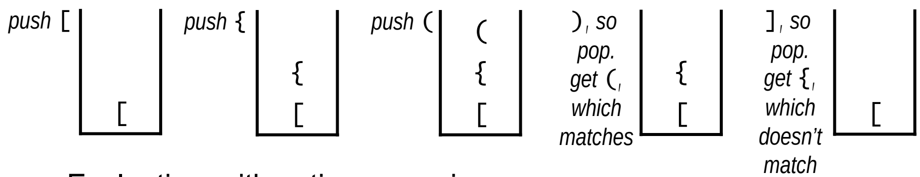
Efficiency of the Stack Implementations

	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

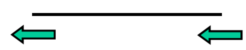
- Converting a recursive algorithm to an iterative one
  - use a stack to emulate the runtime stack
- Making sure that delimiters (parens, brackets, etc.) are balanced:
  - push open (i.e., left) delimiters onto a stack
  - when you encounter a close (i.e., right) delimiter, pop an item off the stack and see if it matches
  - example:

```
5 * [3 + {(5 + 16 - 2)]
```



- Evaluating arithmetic expressions

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

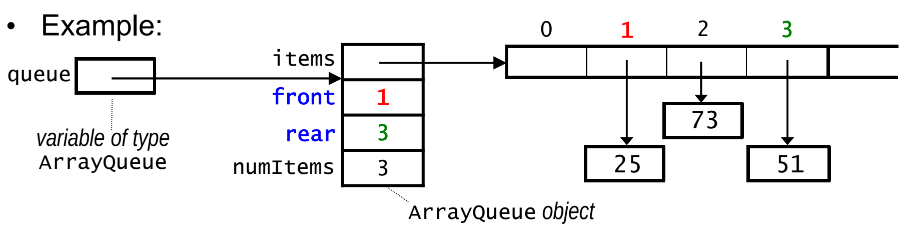
```
public interface Queue<T> {
    boolean insert(T item);
    T remove();
    T peek();
    boolean isEmpty();
    boolean isFull();
}
```

- `insert()` returns `false` if the queue is full, and `true` otherwise.
- `remove()` and `peek()` take no arguments, because we 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 two:

		front					rear
		21	17	89	65	43	81

  we have room for more items, but shifting to make room is inefficient

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

  insert 5: wrap around!

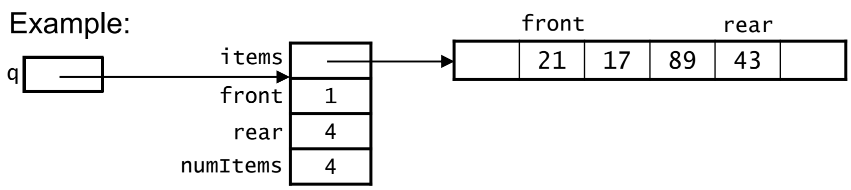
rear		front					
5		21	17	89	65	43	81

Maintaining a Circular Queue

- We use the mod operator (%) when updating `front` or `rear`:

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

- Example:

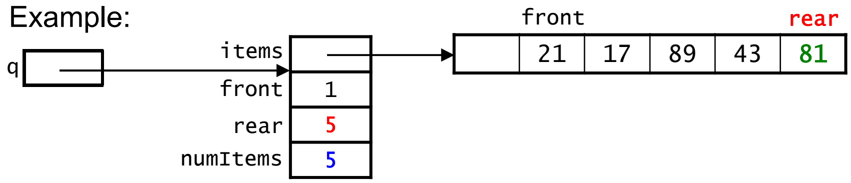


Maintaining a Circular Queue

- We use the mod operator (%) when updating `front` or `rear`:

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

- Example:



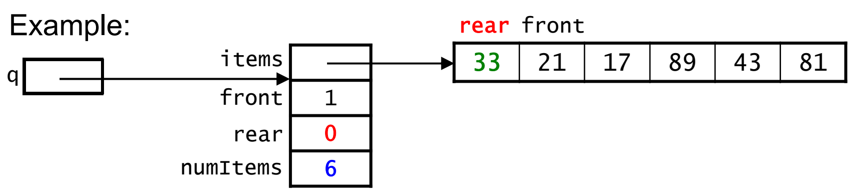
- `q.insert(81):    // rear is not at end of array`
  -
```
rear = (rear + 1) % items.length;
     = (  4  + 1) %       6
     =          5 %       6  = 5 (% has no effect)
```

Maintaining a Circular Queue

- We use the mod operator (%) when updating `front` or `rear`:

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

- Example:

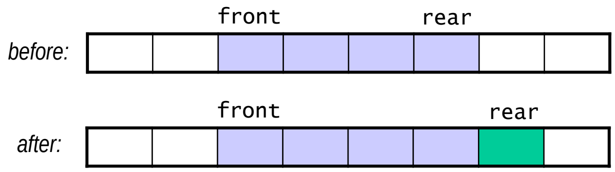


- `q.insert(81):    // rear is not at end of array`
  -
```
rear = (rear + 1) % items.length;
     = (  4  + 1) %       6
     =          5 %       6  = 5 (% has no effect)
```

- `q.insert(33):    // rear is at end of array`
  -
```
rear = (rear + 1) % items.length;
     = (  5  + 1) %       6
     =          6 %       6  = 0    wrap around!
```

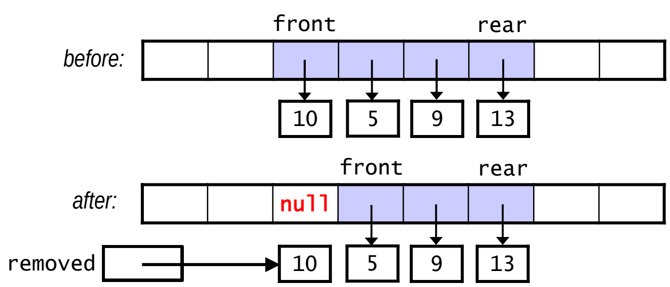
Inserting an Item in an `ArrayQueue`

- We increment `rear` before adding the item:




```
public boolean insert(T item) {
    // code to check for a null item goes here
    if (isFull()) {
        return false;
    }
    rear = (rear + 1) % items.length;
    items[rear] = item;
    numItems++;
    return true;
}
```

`ArrayQueue remove()`

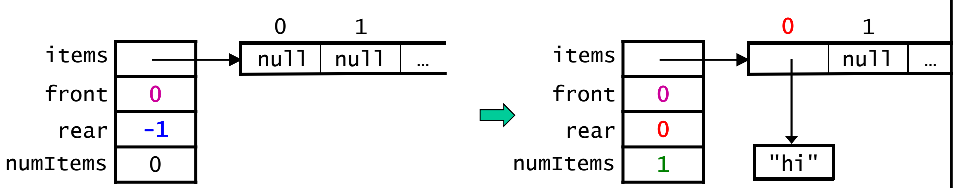



```
public T remove() {
    if (isEmpty()) {
        return null;
    }
    T removed = _________________;


    numItems--;
    return removed;
}
```

Constructor

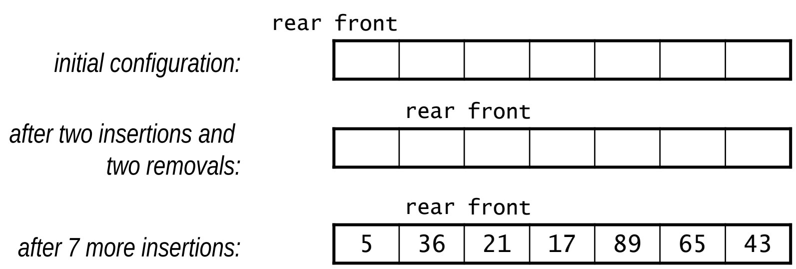
```
public ArrayQueue(int maxSize) {
     // code to check for an invalid maxSize goes here...
     items = (T[])new Object[maxSize];
     front = 0;
     rear = -1;
     numItems = 0;
}
```

- When we insert the first item in a newly created `ArrayQueue`, we want it to go in position 0. Thus, we need to:
  - start `rear` at `-1`, since then it will be incremented to 0 and used to perform the insertion
  - start `front` at `0`, since it is not changed by the insertion



Testing if an `ArrayQueue` is Empty or Full

- In both empty and full queues, `rear` is one "behind" `front`:



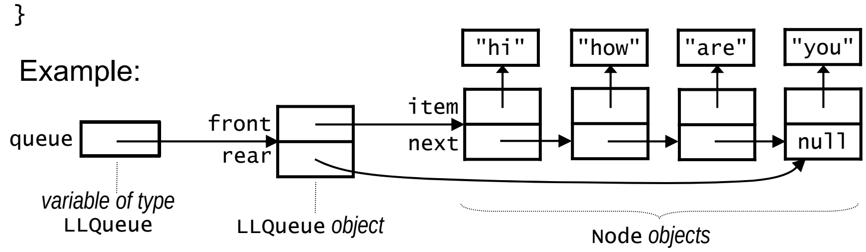
- This is why we maintain `numItems`!

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

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

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:

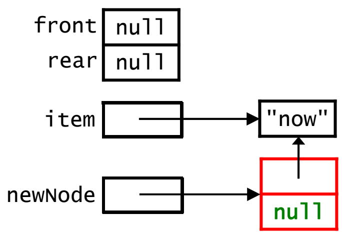


- In a linked list, we can efficiently:
  - remove the item at the front
  - add an item to the rear (if we have a ref. to the last node)
- Thus, this implementation is simpler than the array-based one!

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

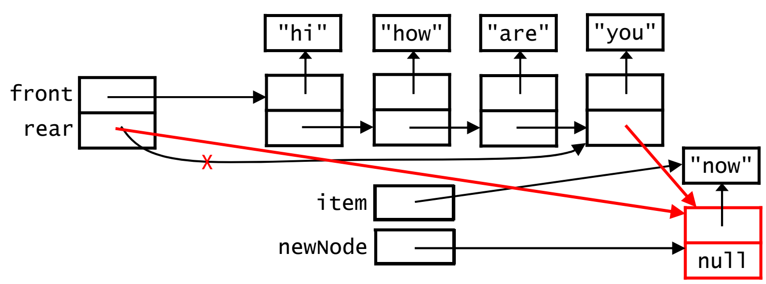
Inserting an Item in an Empty LLQueue



The `next` *field in the* `newNode` *will be* `null` *regardless of whether the queue is empty. Why?*

```
public boolean insert(T item) {
    // code to check for a null item goes here
    Node newNode = new Node(item, null);
    if (isEmpty()) {
        front = newNode;
        rear = newNode;
    } else {
        // we'll add this later!

    }
    return true;
}
```

Inserting an Item in a Non-Empty LLQueue




```
public boolean insert(T item) {
    // code to check for a null item goes here
    Node newNode = new Node(item, null);
    if (isEmpty()) {
        front = newNode;
        rear = newNode;
    } else {


    }
    return true;
}
```

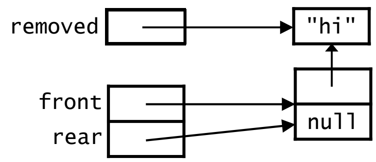
A. `rear = newNode;`
   `rear.next = newNode;`

B. `rear.next = newNode;`
   `rear = newNode;`

C. either A or B

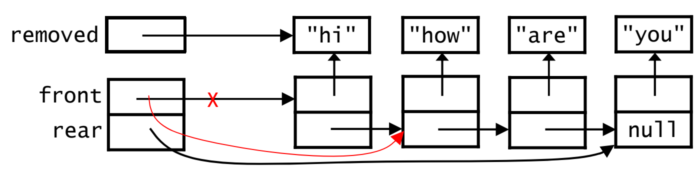
D. neither A nor B

Removing from an `LLQueue` with One Item




```
public T remove() {
    if (isEmpty()) {
        return null;
    }
    T removed = _________________;
    if (front == rear) {      // removing the only item
        front = null;
        rear = null;
    } else {
        // we'll add this later
    }
    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
        front = null;
        rear = null;
    } 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.