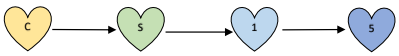
1

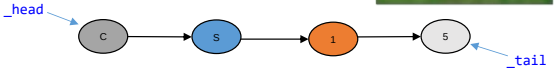
Lecture 16

Linked Lists



2

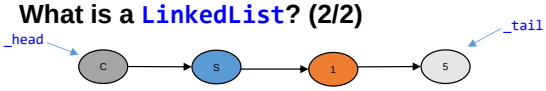
What is a `LinkedList`? (1/2)



- A collection of nodes stored anywhere in memory that are linked in a "daisy chain" to form a sequence of elements
  - as with `Array`s and `ArrayList`s, it can represent an unordered set or an ordered (sorted) sequence of your data elements
- A `LinkedList` holds a reference (pointer) to its first node (*head)* and its last node (*tail*) – the internal nodes maintain the list via their references to their next nodes

3

What is a `LinkedList`? (2/2)



- Each node holds an **element** and a **reference** to the next node in the list
- Most methods will involve:
  - "pointer-chasing" through the `LinkedList` (for `search` and finding the correct place to insert or delete)
  - breaking and resetting the `LinkedList` to perform insertion or deletion of nodes
- But there won't be data movement! Hence efficient for dynamic collections

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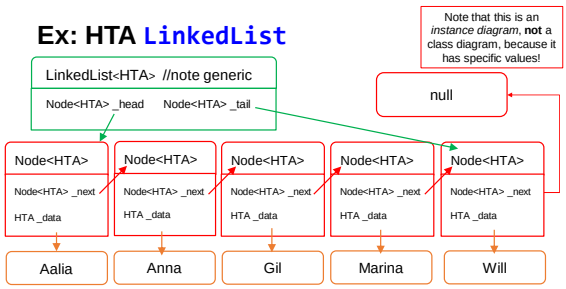
Ex: HTA `LinkedList`



5

When to Use Different Data Structures for Collections (1/3)

- `ArrayList`s get their name because they implement Java-FX's `List` interface (defined soon) and are implemented using `Array`s
- We define a building block called `LinkedList`, an alternative to `ArrayList`s that avoids data movement for insertion and deletion
  - by using pointer manipulation rather than moving elements in an array

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When to Use Different Data Structures for Collections (2/3)

- Using `LinkedList` of `Node`s, we can construct higher level abstractions to model collections (e.g., `NodeList` to parallel `ArrayList`, as well as `Stack`s, `Queue`s, etc.)
- Each `Node` instance holds the data for that element in the list

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When to Use Different Data Structures for Collections (3/3)

- How to decide between data structures?
  - choose based on the way data is *accessed* and *stored* in your algorithm
  - access and store operations of different data structures can have very different impacts on an algorithm's overall efficiency–recall Big-O analysis
  - even without N very large, there can be significant performance differences
  - roughly, `Arrays` if mostly static collection, `ArrayLists` if need more update dynamics, and `LinkedList` if more updates than searches

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Data Structure Comparison

Note: don't usually access items by index in an `ArrayList`; use search/get!

`Array`

- Indexed (explicit access to i^{th} item)
- If user moves elements during insertion or deletion, their indices will change correspondingly
- Cannot change size dynamically

`ArrayList`

- Indexed (explicit access to i^{th} item)
- Indices of successor items automatically updated following an inserted or deleted item
- Can grow/shrink dynamically
- Java uses an `Array` as the underlying data structure (and does the data shuffling)

`LinkedList`

- **Not** indexed – to access the n^{th} element, must start at the beginning and go to the next node n times → no random access!
- Can grow/shrink dynamically
- Uses nodes instead of `Array`s
- Can insert or remove nodes anywhere in the list without data movement through the rest of the list

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Linked List Implementations

- Find java.util implementation at: http://docs.oracle.com/javase/7/docs/api/java/util/LinkedList.html
- To learn list processing, we are going to make our own implementation of this data structure, `MyLinkedList`:
  - difference between `MyLinkedList` and Java's implementation is that Java uses something like our `MyLinkedList` to build a more advanced data structure that implements `List`
  - while there is overlap, there are also differences in the methods provided, their names, and their return types
  - you should use Java's `LinkedList` in your own programs
- `MyLinkedList` is a general building block for more specialized versions we'll build: `Stack`s, `Queue`s, Sorted Linked Lists…
- We'll start by defining a **Singly Linked List** for both unsorted and sorted items, then we'll define a **Doubly Linked List** – users of this data structure don't see any of these internals!

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Generic Unsorted Singly Linked List (1/3)

- Constructor initializes instance variables
  - `_head` and `_tail` are initially set to null
  - `_size` set to 0
- `addFirst` creates first `Node` and updates `_head` to reference it
- `addLast` appends a `Node` to the end of the list and updates `_tail` to reference it

```
public class MyLinkedList<Type> {
    private Node<Type> _head;
    private Node<Type> _tail;
    private int _size;

    public MyLinkedList() {
        _head = null;
        _tail = null;
        _size = 0;
    }
    public Node<Type> addFirst(Type el) {
        //...
    }
    public Node<Type> addLast(Type el) {
        //...
    }

    // more on next slide
}
```

***Generic* – we literally code** "<Type>" as a placeholder for the type chosen by the user of this data structure (ex.: `MyLinkedList<Integer>`, Java substitutes `Integer` where `Type` is)

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Generic Unsorted Singly Linked List (2/3)

- `removeFirst` removes first `Node` and returns element
- `removeLast` removes last `Node` and returns element
- `remove` removes the first occurrence of a `Node` containing the element `el` and returns it

```
public Node<Type> removeFirst() {
    //...
}

public Node<Type> removeLast() {
    //...
}

public Node<Type> remove(Type el) {
    //...
}


// still more on next slide
```

Note: we have aligned methods of `LinkedList` and `ArrayList` where possible, with methods differing as the data structures differ (i.e., `ArrayList` has no `removeLast()` since you can get the last element with index = length-1)

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Generic Unsorted Singly Linked List (3/3)

- `search` finds and returns the `Node` containing `el` or `null` (note the difference with `remove`)
- `size` returns `_size` of the list
- `isEmpty` checks if the list is empty
- `getHead/getTail` return a reference to the head/tail `Node` of the list

```
public Node<Type> search(Type el) {
    //...
}
public int size() {
    //...
}
public boolean isEmpty() {
    //...
}
public Node<Type> getHead() {
    //...
}
public Node<Type> getTail() {
    //...
}
```


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Generic Singly Linked List Summary

```
public class MyLinkedList<Type> {
    private Node<Type> _head;
    private Node<Type> _tail;
    private int _size;

    public MyLinkedList() {
        //...
    }

    public Node<Type> addFirst(Type el) {
        //...
    }

    public Node<Type> addLast(Type el) {
        //...
    }

    public Node<Type> removeFirst() {
        //...
    }

    public Node<Type> removeLast() {
        //...
    }
}
```

```
public Node<Type> remove(Type el) {
    //...
}

public Node<Type> search(Type el) {
    //...
}

public int size() {
    //...
}

public boolean isEmpty() {
    //...
}

public Node<Type> getHead() {
    //...
}

public Node<Type> getTail() {
    //...
}
```


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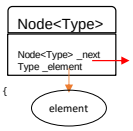
The `Node` Class

- Also uses generics; user of LL specifies type and Java substitutes the specified type in the Node class' methods
- Constructor initializes instance variables `_element` and `_next`
- Its methods are made up of accessors and mutators for these variables:
  - `getNext()` and `setNext()`
  - `getElement()` and `setElement()`

```
public class Node<Type> {
    private Node<Type> _next;
    private Type _element;

    public Node(Type element) {
        _next = null;
        _element = element;
    }

    public Node<Type> getNext() {
        return _next;
    }

    public void setNext(Node<Type> next) {
        _next = next;
    }

    public Type getElement() {
        return _element;
    }

    public void setElement(Type element) {
        _element = element;
    }
}
```



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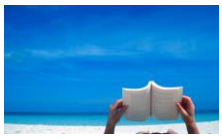
Ex: A pile of Books (1/2)

- Before implementing `LinkedList` internals, let's see how to use one to model a simple unorganized pile (i.e., set) of `Book`s
  - "user" here is another programmer
- The elements in our pile will be of type `Book`
  - each has title, author(s), date and ISBN number
  - we want a list that can store anything that "is a" `Book`



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Ex: A pile of Books (2/2)

- The `Book` class combines Authors, Titles and ISBNs (International Standard Book Number)
- In our Linked List, the `Node`'s element will be of type `Book`

Book

`String _author`
`String _title`
`int _isbn`

`getAuthor()`
`getTitle()`
`getISBN()`
…

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Book Class

- Constructor stores author, date and ISBN number of `Book` as instance variables
- For each property, its `get` method returns that property's value
  - ex. `getISBN()` returns `_isbn`

```
public class Book {
    private String _author;
    private String _title;
    private int _isbn;

    public Book(String author,
                String title, int isbn) {
        _author = author;
        _title = title;
        _isbn = isbn;
    }

    public int getISBN(){
        return _isbn;
    }

    //other mutator and accessor
    //methods elided
}
```


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`PileOfBooks` Class

- Contains a `MyLinkedList` of books as underlying data structure–it's a "thin wrapper"
- `Book` specializes generic `Type`
- Instantiating a `MyLinkedList` is entirely similar to instantiating an `ArrayList`

```
public class PileOfBooks {
    private MyLinkedList<Book> _books;

    public PileOfBooks() {
        _books = new MyLinkedList<Book>();
    }

    //There could be many more methods here!
    //add and search methods on next slide.

}
```


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`PileOfBooks` Class: `add` And `search`

- Since `PileOfBooks` instantiates a `MyLinkedList` of books, the class has access to `MyLinkedList`'s methods
- We can make calls to these in the definitions of `PileOfBooks`' own methods
  - `PileOfBooks`' methods are "wrappers" over the underlying methods from `MyLinkedList`

```
public void addBook(Book myBook) {
    _books.add(myBook);
    //Explanation of add to come!
}

public Node<Book> searchBook(Book myBook) {
    return _books.search(myBook);
    //Explanation of search to come!
}

//There could be many more methods here!
```


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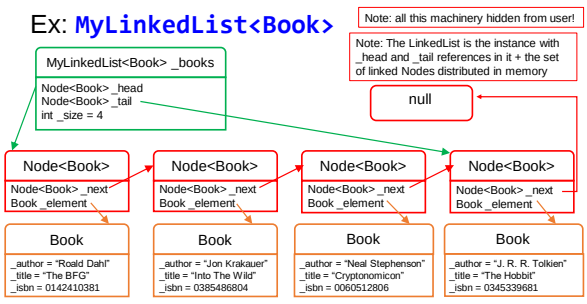
Ex: `MyLinkedList<Book>`



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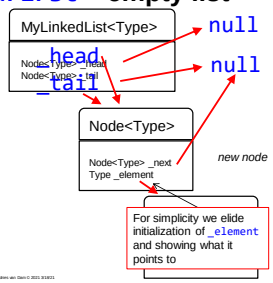
Implementation: `addFirst` – empty list

- If list is empty, `_head` and `_tail` are `null`
  - let's only show the list pointers
- Create a new `Node<ElementType>`
- Update new node's `_next` variable to `null`, which is where current `_head` and `_tail` point in this case
- Update the `_head` and `_tail` variables to the new node



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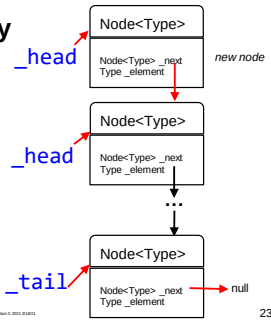
`addFirst` – non empty

- Construct new `Node`
- Initialize its `_next` variable to current `_head` (in this case, some previously added `Node` that headed list)
- Update LL's `_head` variable to the new `Node`



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Constructor and `addFirst` Method (1/2)

- Constructor — as shown before
  - initialize instance variables
- `addFirst` method
  - increment `_size` by 1
  - create new `Node` ((S14: its constructor stores `el` in `_element`, `null` in `_next`)
  - update `newNode`'s `_next` to first `Node` (pointed to by `_head`)
  - update LL's `_head` to point to `newNode`
  - if `_size` is 1, `_tail` must also point to `newNode`
  - return `newNode`

```
public MyLinkedList() {
    _head = null;
    _tail = null;
    _size = 0;
}

public Node<Type> addFirst(Type el) {
    _size++;
    Node<Type> newNode = new Node<Type>(el);
    newNode.setNext(_head); //previous head
    _head = newNode;

    if (size == 1) {
        _tail = newNode;
    }

    return newNode;
}
```


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Constructor and `addFirst` Runtime (2/2)

```
public MyLinkedList() {
    _head = null;                                   // 1 op
    _tail = null;                                   // 1 op
    _size = 0;                                      // 1 op
}                                                   → constructor is O(1)

public Node<Type> addFirst(Type el) {
    _size++;                                        // 1 op
    Node<Type> newNode = new Node<Type>(el);        // 1 op
    newNode.setNext(_head);                         // 1 op
    _head = newNode;                                // 1 op

    if (size == 1){                                 // 1 op
        _tail = newNode;                            // 1 op
    }
    return newNode;                                 // 1 op
}                                                   → addFirst(Type el) is O(1)
```


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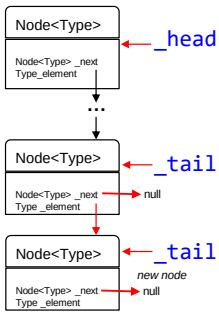
`addLast` Method (1/2)

- LL's `_tail` already points to the last `Node` in the list
- Create a new `Node<Type>`
- Update `_tail`'s node's `_next` pointer to the new node
- Then, update `_tail` to the new `Node`



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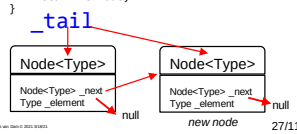
`addLast` Method (2/2)

- Edge Case
  - if list is empty, update the `_head` and `_tail` variables to the `newNode`
- General Case
  - update `_next` of current last `Node` (to which `_tail is pointing –` "update `_tail's _next`") to new last `Node`
  - update `_tail` to that new last `Node`
  - new `Node`'s `_next` variable already points to `null`

```
public Node<Type> addLast(Type el) {
    Node<Type> newNode = new Node<Type>(el)
    if (_size == 0) {
        _head = newNode;
        _tail = newNode;
    }
    else {
        _tail.setNext(newNode);
        _tail = newNode;
    }
    _size++;
    return newNode;
}
```



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`addLast` Runtime

```
public Node<Type> addLast(Type el) {
    Node<Type> newNode = new Node<Type>(el)          // 1 op
    if (_size == 0) {                                // 1 op
        _head = newNode;                             // 1 op
        _tail = newNode;                             // 1 op
    }
    else{
        _tail.setNext(newNode);                      // 1 op
        _tail = newNode;                             // 1 op
    }
    _size++;                                         // 1 op
    return newNode;                                  // 1 op
}
```

→ `addLast(Type el)` is O(1)

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`size` and `isEmpty` Methods

```
public int size() {
    return _size;
}

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

isEmpty() would return false

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`size` and `isEmpty` Runtime

```
public int size() {
    return _size;                    // 1 op
}

public boolean isEmpty() {
     return _size == 0;              // 1 op
}
```

→ `size()` is O(1)

→ `isEmpty()` is O(1)

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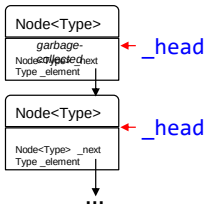
`removeFirst` Method (1/2)

- Remove reference to original first `Node` by setting `_head` variable to second `Node`, i.e., first `Node`'s successor `Node`, via first's `_next`
- `Node` to remove is garbage-collected after the termination of the method



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`removeFirst` Method (2/2)

- Edge case for empty list
  - `println` is optional, just one way to handle error checking; caller should check for null in any case
- Store data element from first `Node` to be `removed`
- Then unchain first `Node` by resetting `_head` to point to first `Node`'s successor
- If list is *now* empty, update `_tail` to `null` (what did `_head` get set to?)
- `Node` to remove is garbage-collected at method's end

```
public Type removeFirst() {
    if (_size == 0) {
        System.out.println("List is empty");
        return null;
    }

    Type removed = _head.getElement();
    _head = _head.getNext();
    _size--;
    if (_size == 0) {
        _tail = null;
    }
    return removed;
}
```


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`removeFirst` Runtime

```
public Type removeFirst() {
    if (_size == 0) {                          // 1 op
        System.out.println("List is empty");   // 1 op
        return null;                           // 1 op
    }

    Type removed = _head.getElement();         // 1 op
    _head = _head.getNext();                   // 1 op
    _size--;                                   // 1 op
    if (_size == 0) {                          // 1 op
        _tail = null;                          // 1 op
    }
    return removed;                            // 1 op
}
```

→ `removeFirst()` is O(1)

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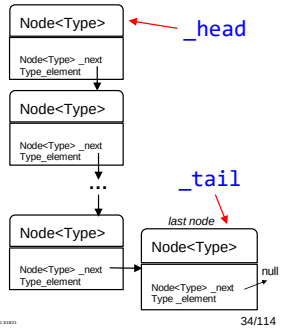
Review: Accessing Nodes Via Pointers

`_head.getNext();`

- This does not get the `_next` field of `_head`, which doesn't have such a field, being just a pointer
- Instead, it is the temporary name of a `node` and `getNext()` gets that node's `_next` field, a pointer to the second node
- What does `_tail.getNext()` produce?
- What does `_tail.getElement()` produce?
- note we can access a variable by its unique name, its index, its contents, or here, via a pointer



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Lecture Question

Given a `Linked List` of `Nodes`,

`A -> B -> C -> D`

where `_head` points to node `A`, what is `_head.getNext().getNext()`?

A. Nothing, throws a `NullPointerException`
B. `C`
C. `B`
D. `D`

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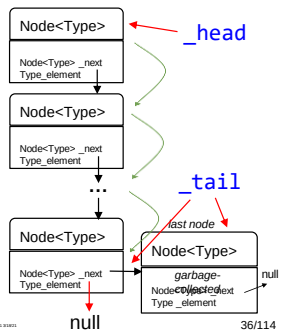
`removeLast` Method

- As with `removeFirst`, remove `Node` by removing any references to it. Need to know predecessor, but no pointer to it!
- Pointer-chase in a loop to get predecessor to `_tail` and reset predecessor's `_next` instance variable to null
  - very inefficient–stay tuned
- Update `_tail`
- Last `Node` is thereby garbage-collected!



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`removeLast` Method

- Edge case(s)
  - can't delete from an empty list
  - if there is only one `Node`, update `_head` and `_tail` references to `null`
- General case
  - iterate ("pointer-chase") through list – common pattern using pointers to current and previous node in lockstep
  - after loop ends, `prev` will point to `Node` just before last `Node` and `curr` will point to last `Node`

```
public Type removeLast() {
    Type removed = null;
    if (_size == 0) {
        System.out.println("List is empty");
    }
    else if (_size == 1) {
        removed = _head.getElement();
        _head = null;
        _tail = null;
        _size = 0;
    }
    else { //classic pointer-chasing loop
        Node curr = _head;
        Node prev = null;
        while (curr.getNext() != null) {
            //bop the pointers
            prev = curr;
            curr = curr.getNext();
        }
        removed = curr.getElement();
        prev.setNext(null); //unlink last
        _tail = prev; //update _tail
        _size--;
    }
    return removed;
}
```


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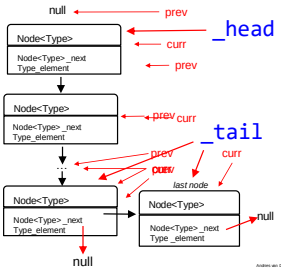
`removeLast` Method




```
public Type removeLast() {
    Type removed = null;
    if (_size == 0) {
        System.out.println("List is empty");
    }
    else if (_size == 1) {
        removed = _head.getElement();
        _head = null;
        _tail = null;
        _size--;
    }
    else { //classic pointer-chasing loop
        Node curr = _head;
        Node prev = null;
        while (curr.getNext() != null) {
            //bop the pointers
            prev = curr;
            curr = curr.getNext();
        }
        removed = curr.getElement();
        prev.setNext(null); //unlink last
        _tail = prev; //update _tail
        _size--;
    }
    return removed;
}
```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`removeLast` Runtime

```
public Type removeLast() {
    Type removed = null;                    // 1 op
    if(_size == 0) {                        // 1 op
        System.out.println("List is empty"); // 1 op
    }
    else if(_size == 1) {                   // 1 op
        removed = _head.getElement();       // 1 op
        _head = null;                       // 1 op
        _tail = null;                       // 1 op
        _size--;                            // 1 op
    }
    else{
        Node curr = _head;                  // 1 op
        Node prev = null;                   // 1 op
        while (curr.getNext() != null) {    // n ops
            prev = curr;                    // 1 op
            curr = curr.getNext();          // 1 op
        }
        removed = curr.getElement();        // 1 op
        prev.setNext(null);                 // 1 op
        _tail = prev;                       // 1 op
        _size--;                            // 1 op
    }
    return removed;                         // 1 op
}
```

→ `removeLast()` is O(n)

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Lecture Question

Given that `_animals` is a Singly Linked List of ***n*** animals already in the list, what would be printed to the console?

```
private void testListMethods() {

    _animals.addFirst(new Cat());
    _animals.addFirst(new Fish());
    _animals.addLast(new Dog());
    if(!_animals.isEmpty()) {
         System.out.println("Not Empty");
    }
    System.out.println(_animals.removeLast());

}
```

A. "Not Empty", "Dog"
B. no print, "Cat"
C. "Not Empty", "Fish"
D. no print, "Dog"

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Lecture Question

Given that `_animals` is a Singly Linked List of ***n*** animals, what is `node` pointing to?

```
curr = _head;
prev = null;
while (curr.getNext().getNext() != null) {
    prev = curr;
    curr = curr.getNext();
}
node = curr.getNext();
```

A. Nothing useful, throws a `NullPointerException`
B. Points to the last node on the list
C. Points to the second node on the list
D. Points to the head of the list

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Lecture Question

Given that `_animals` is a Singly Linked List of ***n*** animals, what will this code fragment do?

```
//prev and curr initialized to null and _head, respectively
while (curr.getNext() != null) {
    prev = curr;
    curr = curr.getNext();
}
removed = prev.getElement();
System.out.println(removed);
```

A. Nothing useful, throws a `NullPointerException`
B. Prints last animal in list
C. Prints next to last animal in list
D. Prints whole list

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`search` Method

- Let's think back to our pile of `Books` example – what if we want to find a certain `Book` in the pile of `Book`s? What if we want to search by ISBN, author, or title?

- Must compare each `Book` with one we are looking for
  - but in order to do this, we first need a way to check for the equality of two elements!
  - brute force: we can do somewhat better by sorting, much better with sorted arrays, binary trees – stay tuned!

Java's `Comparable<Type>` interface (1/3)

- Previously we used `==` to check if two things are equal
  - this only works correctly for primitive data types (e.g., `int`), or when we are comparing two variables referencing the exact same object
  - to compare `String`s, need a different way to compare things
- We can implement the `Comparable<Type>` generic interface provided by Java
- Must define `compareTo` method, which returns an `int`
- Why don't we just use ==, even when using something like ISBN, which is an `int`?
  - can treat ISBNs as `int`s and compare them directly, but more generally we implement the `Comparable<Type>` interface, which could easily accommodate comparing `String`s, such as author or title, or any other property

Java's `Comparable<Type>` interface (2/3)

- The `Comparable<Type>` interface is specialized (think of it as parameterized) using generics

```
public interface Comparable<Type> {
    public int compareTo(Type toCompare);
}
```

- Call `compareTo` on a variable of same type as specified in implementator of interface (`Book`, in our case)
  - `currentBook.compareTo(bookToFind);`
  - pseudo-code: `currentBook?bookToFind`

Java's `Comparable<Type>` interface (3/3)

- `compareTo` method must return an `int`
  - **negative** if element on which `compareTo` is called is *less* than element passed in as the parameter of the search
  - **0** if element is *equal* to element passed in
  - **positive** if element is *greater* than element passed in
  - sign of `int` returned is all-important, magnitude is not and is implementation dependent
- `compareTo` not only used for numerical comparisons–it could be used for alphabetical or geometric comparisons as well–depends on how you implement `compareTo`

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"Comparable" `Book` Class

- Recall format for `compareTo`:
  - `elementA.compareTo(elementB)`
- Book class now implements `Comparable<Book>`
  - this means we can compare books, using `bookA.compareTo(bookB)`
- `compareTo` is defined according to these specifications
  - returns number that is `<0`, `0` or `>0`, depending on the ISBN numbers
  - <0 if stored `_isbn` < `toCompare` parm

```
public class Book implements Comparable<Book> {

    // variable declarations, e.g. _isbn, elided
    public Book(String author, String title,
                int isbn){
        //variable initializations elided
    }

    public int getISBN(){
        return _isbn;
    }

    //other methods elided

    //compare isbn of book passed in to stored one
    @Override
    public int compareTo(Book toCompare){
        return (_isbn - toCompare.getISBN());
    }
}
```


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"Comparable" Singly Linked List

In our example use `Book` as `Type`

- Using keyword `extends` in this way ensures that `Type` implements `Comparable<Type>`
  - note nested <>, and that `extends` is used differently from inheritance notation
  - nested <> to show it modifies `Type` and not the class
- All elements stored in `MyLinkedList` must now have `compareTo` method for `Type`; thus restricts generic

Just as classes "extend" other classes, interfaces can "extend" other interfaces, thus generic `Type` must "extend" the interface

```
public class MyLinkedList<Type extends
                          Comparable<Type>>{
    private Node<Type> _head;
    private Node<Type> _tail;
    private int _size;

    public MyLinkedList() {
        //...
    }
    public Node<Type> addFirst(Type el) {
        //...
    }
    public Node<Type> addLast(Type el) {
        //...
    }
    // other methods elided
}
```


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`search` Method for `MyLinkedList` (brute force)

- Loops through list until element is found or end is reached (`curr==null`)
- If a `Node`'s element is same as the input, `return curr` (note: returning always exits a method)
- If no elements match, `return null`

```
public Node<Type> search(Type el) {
    Node<Type> curr = _head;

    while (curr != null) {
        if (curr.getElement().compareTo(el) == 0) {
            return curr;
        }
        curr = curr.getNext(); //bop pointer
    }

    return null; //got to end of list w/o finding
}
```


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`search` Runtime

```
public Node<Type> search(Type el) {
    Node<Type> curr = _head;                        // 1 op

    while (curr != null) {                          // n ops
        if (curr.getElement().compareTo(el) == 0) {  // 1 op
            return curr;                            // 1 op
        }
        curr = curr.getNext();                      // 1 op
    }

    return null;                                    // 1 op
}
```

→ `search(Type el)` is O(n)

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`remove` Method

- We have implemented methods to remove the first and the last `element`s of `MyLinkedList`
- What if we want to remove *any* `element` from `MyLinkedList`?
- Let's write a general `remove` method
  - think of it in 2 phases:
    - a search loop to find the right element (or end of list)
    - breaking the chain to jump over the element to be removed

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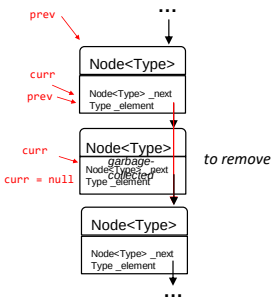
`remove` Method

- Loop through `Node`s until an `_element` matches `itemToRemove`
- "Jump over" `Node` by re-linking predecessor of `Node` (again using loop's `prev` pointer) to successor of `Node` (via its `_next` reference)
- With no more reference to `Node`, it is garbage collected at termination of method



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`remove` Method

- Edge Case(s)
  - again: can't delete from an empty list
  - if removing first item or last item, delegate to `removeFirst`/`removeLast`
- General Case
  - iterate over list until `itemToRemove` is found in ptr-chasing loop
  - again: need `prev`, so we can re-link predecessor of `curr`. Node is GC'd upon `return`.

Note: caller of remove can find out if item was successfully found (and removed) by testing for `!= null`

```
public Type remove(Type itemToRemove){
    if (this.isEmpty()) {
        System.out.println("List is empty");
        return null;
    }

    if (itemToRemove.compareTo(_head.getElement()) == 0) {
        return this.removeFirst();
    }

    if (itemToRemove.compareTo(_tail.getElement()) == 0) {
        //loop to get tail's predecessor
        return this.removeLast();
    }

    Node<Type> curr = _head.getNext(); //advance to 2nd item
    Node<Type> prev = _head;
    while (curr != null) {//pointer-chasing loop to find el.
        if (curr.getElement().compareTo(itemToRemove) == 0) {
            prev.setNext(curr.getNext()); //jump over node
            _size--; //decrement size
            return curr.getElement();
        }
        prev = curr; //if not found, bop pointers
        curr = curr.getNext();
    }

    return null; //return null if itemToRemove is not found
}
```


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`remove` Runtime

```
public Type remove(Type itemToRemove){
    if (this.isEmpty()) {                                   // 1 op
        System.out.println("List is empty");                // 1 op
        return null;
    }
    if (itemToRemove.compareTo(_head.getElement()) == 0) {  // 1 op
        return this.removeFirst();                          // O(1)
    }
    if (itemToRemove.compareTo(_tail.getElement()) == 0) {  // 1 op
        return this.removeLast();                           // O(n) pointer chase till list end
    }
    Node<Type> curr = _head.getNext();                      // 1 op
    Node<Type> prev = _head;                                // 1 op
    while (curr != null) {                                  // n ops
        if (itemToRemove.compareTo(curr.getElement()) == 0) {// 1 op
            prev.setNext(curr.getNext());                   // 1 op
            _size--;                                        // 1 op
            return curr.getElement();                       // 1 op
        }
        prev = curr;                                        // 1 op
        curr = curr.getNext();                              // 1 op
    }
    return null;                                            // 1 op
}
```

→ `remove(Type itemToRemove)` is O(n)

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Lecture Question

Given that `_animals` is a Singly Linked List of ***n*** animals, `curr` points to the node with an animal to be removed from the list, and that `prev` points to `curr`'s predecessor, what will this code fragment do?

```
removed = curr.getElement();
prev.setNext(curr.getNext());
temp = prev.getNext();
System.out.println(temp.getElement());
```

A. List is unbroken, prints out removed animal
B. List is broken, prints out removed animal
C. List loses an animal, is intact, and prints out removed animal
D. List loses an animal, is intact, and prints out the animal after the one that was removed

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Ex: A sorted bookshelf

- Faster to find (and remove!) books in a *sorted* bookshelf
- Use a *sorted* linked list
  - makes several of our methods somewhat more efficient:
    - `search`
    - `insert`
    - `delete`
- Sort in increasing order
  - maintain sort order when inserting

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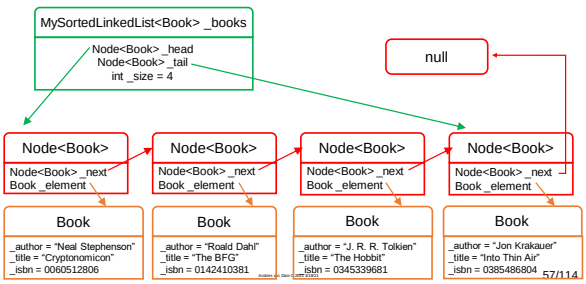
Ex: `MySortedLinkedList<Book>`



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Generic Sorted Singly Linked List

- Slightly different set of methods
  - `addFirst` and `addLast` replaced by general `insert`
- Many methods whose signatures are identical to those of the unsorted list will have different implementation because of more efficient loop termination used in `search` and `remove`

```
public class MySortedLinkedList<Type> {
    private Node<Type> _head;
    private Node<Type> _tail;
    private int _size;

    public MySortedLinkedList() {
        //...
    }
    public Node<Type> insert(Type el) {
        //...
    }
    public Type remove(Type el) {
        //...
    }
    public Node<Type> search(Type el) {
        //...
    }
    public int size() {
        //...
    }
    public boolean isEmpty() {
        //...
    }
    public Node<Type> getHead() {
        //...
    }
    public Node<Type> getTail() {
        //...
    }
}
```


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`search` Method [For Sorted Linked Lists]

- Must iterate through list until `toFind` is found – only need `curr`
- Compare `toFind` to `curr`'s element
  - if equal, we're done!
- If `curr`'s element is greater than `toFind`, stop search
  - any following `Node`'s elements will also be greater since list is sorted
  - note: order of operands dictates sign of test–be careful!

```
public Node<Type> search(Type toFind){
    Node<Type> curr = _head;
    while (curr != null) {
        //have we found it?
        if (curr.getElement().compareTo(toFind) == 0) {
            return curr;
        }
        //are we past it? Curr's element > toFind
        else if (curr.getElement().compareTo(toFind) > 0){
            return null;
        }
        //haven't found it, hop the curr
        curr = curr.getNext();
    }

    return null;
}
```


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`search` Runtime [For Sorted Linked Lists]

```
public Node<Type> search(Type toFind) {
    Node<Type> curr = _head;                          // 1 op
    while (curr != null) {                            // n ops

        if (curr.getElement().compareTo(toFind) == 0) { // 1 op
            return curr;                              // 1 op
        }
        else if (curr.getElement().compareTo(toFind) > 0) { // 1 op
            return null;                              // 1 op
        }

        curr = curr.getNext();                        // 1 op
    }

    return null;                                      // 1 op
}
```

→ `search(Type toFind)` is O(n)

While the `else if` statement will typically improve performance because searches don't usually have to search to the bitter end, it does *not* affect Big-O run time! (Big-O describes the *worst case*!)

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What Did Sorting Buy Us?

- Search still O(n)—not better worst-case performance, but better for normal cases because can usually stop earlier for items not in the list
- This comes at the cost of having to maintain sort order, i.e., by having to insert "in the right place" (next slide)
- So if an algorithm does lot of searching compared to insertion and deletion, this efficiency would pay off; it even beats a sorted array because the linear search loop is O(n) for both sorted linked lists and arrays, but inserting/deleting is O(1) for linked lists and O(n) for arrays because of (worst case) data movement
  - we can do much better than O(n) for search: Binary Search in a sorted array and a Linked List as a Binary Tree makes search O(log n) (stay tuned for Lecture on Trees)
- Conversely, if an algorithm does a lot of adding and deleting compared to searching, sorting wouldn't pay off since the algorithm couldn't use the simple O(1) `insertFirst` or `insertLast`…

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Comparing Variable Values

- The equality operator "`==`" compares references
  - checks if two objects point to the same place in memory
  - good for comparing primitive types (`integers, doubles, booleans`, etc..)
- The "`.equals()`" method compares content
  - checks if two objects have the same values
  - most Java classes override the `.equals()` method to be able to compare instances of themselves
- We will use `.equals()` for `Strings`, but for more general comparisons use the `Comparable<Type>` interface

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Comparisons

```
int x = 5;
int y = 5;
x == y;
true
```

Primitive types assigned to a variable are contained in that variable, hence "`==`" compares the contents

```
String s1 = new String("CS15 is so fun!");
String s2 = new String("CS15 is so fun!");
s1 == s2
false
```

Because "`==`" compares references for non-primitives, therefore use `s1.equals(s2);`

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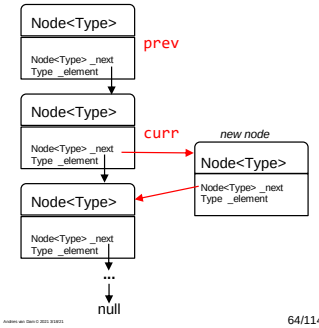
`insert` method

- Once again, 2 phases:
  - find right place to insert with a search loop, keeping track of current and previous nodes
  - break the chain to insert
- Unlike insertion into unsorted linked list, there is one correct spot in sorted list for new node
- End iteration if current node's value is greater than new node's value–break the chain and insert there!
- Update `_next` pointers of new node and previous node



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`insert` Method [for Sorted Linked Lists]

- Edge case
  - if list is empty, all we have to do is reset `_head`/`_tail`
- General case
  - iterate over lists until `curr`'s element is greater than `newItem`
  - need loop's `prev`, so we can re-link list to integrate the new node
  - or if not found, special case

```
public Node<Type> insert(Type newItem){
    Node<Type> toAdd = new Node<Type>(newItem); //node for newItem
    if (this.isEmpty()) {
        _head = toAdd;
        _tail = toAdd;
        return _head;
    }
    else {
        Node<Type> curr = _head;
        Node<Type> prev = null;

        while (curr != null) { //pointer-chasing iterator
            if (curr.getElement().compareTo(newItem) < 0) {
                prev = curr;
                curr = curr.getNext();
            }
            else { //found the spot! Update two pointers
                toAdd.setNext(curr); //always do this, but...
                if (prev != null) { //prev is null only at front
                    prev.setNext(toAdd);
                }
                else {
                    _head = toAdd; //insert at front of list
                }
                _size++
                return toAdd;
            }
        }
        prev.setNext(toAdd); //not found, insert node at end
        _tail = toAdd;
        _size++;
        return toAdd;
    }
}
```


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`insert` Runtime [for Sorted Linked Lists]

```
public Node<Type> insert(Type newItem) {
    Node<Type> toAdd = new Node<Type>(newItem);              // 1 op
    if (this.isEmpty()) {                                    // 1 op
        _head = toAdd;                                       // 1 op
        _tail = toAdd;                                       // 1 op
        return _head;
    }
    else {
        Node<Type> curr = _head;                             // 1 op
        Node<Type> prev = null;                              // 1 op
        while(curr != null){ //pointer-chasing iterator      // n ops
            if (curr.getElement().compareTo(newItem) < 0) {  // 1 op
                prev = curr;                                 // 1 op
                curr = curr.getNext();                       // 1 op
            }
            else {
                toAdd.setNext(curr);                         // 1 op
                if (prev != null) {                          // 1 op
                    prev.setNext(toAdd);                     // 1 op
                }
                else {
                    _head = toAdd;                           // 1 op
                }
                _size++;                                     // 1 op
                return toAdd;                                // 1 op
            }
        }
        prev.setNext(toAdd);                                 // 1 op
        _tail = toAdd;                                       // 1 op
        _size++                                              // 1 op
        return toAdd;                                        // 1 op
    }
}
```

→ `insert(Type newItem)` is O(n)

Note: O(n) is to find the point of insertion

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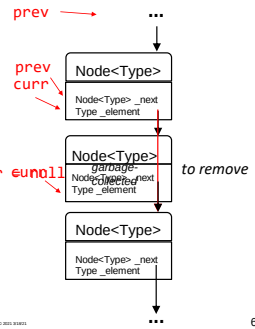
`remove` Method [for Sorted Linked Lists]

- Loop through nodes until an `_element` matches `itemToRemove` is found
  - since list is sorted, we can end loop early–stay tuned
- Re-link predecessor of node (again using a previous node) to successor of node (its `_next` reference)
- With no more reference to node, it is garbage collected at the termination of the method



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`remove` Method [for Sorted Linked Lists]

- Edge Case(s)
  - if list is empty, return `null`
  - if `itemToRemove` is the `_head`/`_tail`, use same code as `removeFirst`/`removeLast` in `MyLinkedList`
- General case
  - iterate over list until either:
    - `itemToRemove` is found (equals `curr`'s element), so reset `next` pointer in `prev` node and return found item
    - or if `curr`'s element is greater than `itemToRemove`, it can't be in the list, hence return `null` → early exit!
    - or we reach end of list, so return `null`

```
public Type remove(Type itemToRemove){
    if (this.isEmpty()) {
        return null;
    }
    if (itemToRemove.compareTo(_head.getElement()) == 0) {
        //elided; same as MyLinkedList's removeFirst code
    }
    if (itemToRemove.compareTo(_tail.getElement()) == 0) {
        //elided; same as MyLinkedLists's removeLast code
    }

    Node<Type> curr = _head.getNext();
    Node<Type> prev = _head;
    while (curr != null) {
        if (curr.getElement().compareTo(itemToRemove) == 0) {
            prev.setNext(curr.getNext()); //jump over node
            _size--;
            return curr.getElement(); //curr points to found
        }
        else if (curr.getElement().compareTo(itemToRemove)>0) {
            return null;
        }
        prev = curr; //bop pointers, iterate
        curr = curr.getNext();
    }
    return null; // End of list, w/o finding it
}
```


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`remove` Runtime [for Sorted Linked Lists]

```
public Type remove(Type itemToRemove){
    if (this.isEmpty()) {                                   // 1 op
        return null;                                        // 1 op
    }
    if (itemToRemove.compareTo(_head.getElement()) == 0) {  // 1 op
        //elided; same as MyLinkedList's removeFirst code   // O(1)
    }
    if (itemToRemove.compareTo(_tail.getElement()) == 0) {  // 1 op
        //elided; same as MyLinkedLists's removeLast code   // O(n)
    }

    Node<Type> curr = _head.getNext();                      // 1 op
    Node<Type> prev = _head;                                // 1 op
    while (curr != null) {                                  // n ops
        if (curr.getElement().compareTo(itemToRemove) == 0) {// 1 op
            prev.setNext(curr.getNext());                   // 1 op
            _size--;                                        // 1 op
            return curr.getElement();                       // 1 op
        }
        else if (curr.getElement().compareTo(itemToRemove) > 0) {// 1 op
            return null;                                    // 1 op
        }
        prev = curr;                                        // 1 op
        curr = curr.getNext();                              // 1 op
    }
    return null;                                            // 1 op
}
```

Again, the `else if` statement will often improve performance, but it does *not* affect Big-O run time

→ `remove(Type itemToRemove)` is O(n)

Note: O(n) is to find the point of removal

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Lecture Question

How do sorted and unsorted Linked Lists differ?

A. Sorted linked lists are somewhat more efficient than unsorted linked lists because they are more quickly searched, but are far less efficient for insertion and deletion.

B. Sorted linked lists are less efficient than unsorted linked lists because they are more slowly searched, but are more efficient for insertion and deletion.

C. Sorted linked lists are more efficient than unsorted linked lists because they are more quickly searched and are more efficient for insertion and deletion.

D. Sorted linked lists are somewhat more efficient than unsorted linked lists, but they are more slowly searched and are far less efficient for insertion and deletion.

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Unsorted vs. Sorted Singly Linked List (1/3)

- Worst Case and Best Case are the same for sorted and unsorted linked lists, as is the average case if the item is in the list (n/2 on average)
- Runtime advantage of sorted list comes when object is not in list (and at cost of more expensive insert/delete)
  - can stop looping if we find an element larger than what we are searching for
  - note: while searching may be on average twice as efficient for this case, big O is still O(n) for worst and average cases

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Unsorted vs. Sorted Singly Linked List (2/3)

- LISP, the original AI programming language, and its various dialects, e.g., Scheme, use linked lists as the basic data structure
- Recursive definition of list: a list member is an atomic element or a sublist

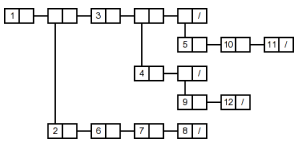

Figure 3: Diagram of cons cells of the simple tree.

Source: http://gajon.org/trees-linked-lists-common-lisp/

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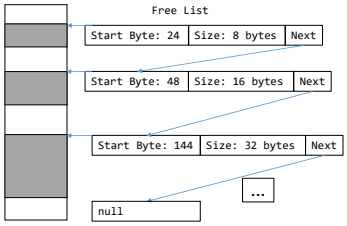
Unsorted vs. Sorted Singly Linked List (3/3)

- Example using a sorted singly linked list: dynamic storage allocation using the "free list"
  - need a dynamic collection, and single pointers are memory efficient
  - can search until we find the smallest chunk of memory large enough for what we need



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Efficiency of Arrays vs. Linked Lists in Modern Computers (1/2)

- Our discussion has not taken into account memory hierarchies
  - (superfast index registers, not suitable for storing more than frequently-used vars)
  - at the lowest level is the cache, which is very fast but limited in size (may have multiple levels, e.g., LI at 32KB, L2 at 256KB and L3 at 2MB for Intel's i7)
  - next is system memory (aka CPU memory, RAM) – much larger, much slower
  - next is peripheral memory such as flash drives, disk drives, etc. – much slower
  - could even consider cloud storage as a 4th level
- Arrays can be stored and accessed super-efficiently as a whole or in chunks in cache, but when a next element isn't in cache, a cache "miss" occurs and the next chunk has to be brought in from RAM, overwriting the previous chunk

From Tom Doeppner's CS33 Lecture:
–... the L1 cache is like grabbing a piece of paper from your desk (3 seconds)
–... the L2 cache is picking up a book from a nearby shelf (14 seconds)
–... main system memory is taking a 4-minute walk down the hall to talk to a friend
–... a hard drive is like leaving the building to roam the earth for one year and three months
http://duartes.org/gustavo/blog/post/what-your-computer-does-while-you-wait/

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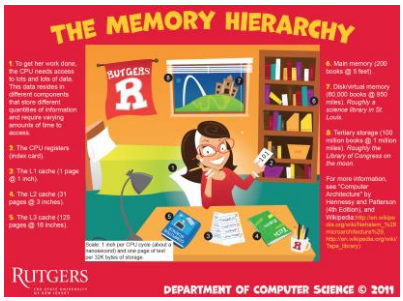

Image courtesy of Michael Littman

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Efficiency of Arrays vs. Linked Lists in Modern Computers (2/2)

- Virtual memory is an even older technique where "pages" of program and/or data are stored in peripheral memory but your program doesn't have to deal with that – page misses/faults cause hardware and the OS to find the proper page in peripheral memory and bring it in
- Linked list traversal may be much more inefficient than simulating dynamic collections with arrays if data movement or copying arrays into larger arrays can largely be done in cache, because page faults are hugely time-consuming (millisecs vs. microseconds)
- Understanding performance of algorithms and data structures for actual data is complex, hardware-dependent, and is different from Big-O asymptotic analysis – they both have their place

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Doubly Linked List (1/3)

- Is there an easier/faster way to get to the previous node while removing a node?
  - with Doubly Linked Lists, nodes have references both to next and previous nodes
  - can traverse list both backwards and forwards – Linked List still stores reference to front of the list with `_head` and back of the list with `_tail`
  - modify `Node` class to have *two* pointers: `_next` and `_prev`

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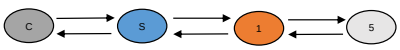
Doubly Linked List (2/3)



- For Singly Linked List, the processing typically goes from first to last node, e.g. `search`, finding the place to insert or delete
- Sometimes, particularly for a sorted list[1], need to go in the opposite direction
  - e.g., we sort CS15 students on their final grades in ascending order. find the lowest numeric grade that will be recorded as an "A". We then ask: who has a lower grade but is close to the "A" cut-off, i.e., in the grey area, and therefore should be considered for "benefit of the doubt"?

[1] like Singly Linked Lists, Doubly Linked Lists can be sorted or unsorted. We only discuss the sorted version here

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Doubly Linked List (3/3)

- This kind of backing-up can't easily be done with the Singly Linked List implementation we have so far
  - could build our own *specialized* `search` method, which would scan from the `_head`, and be, at a minimum, O(n)
- It is simpler for Doubly Linked Lists:
  - find student with the lowest "A" using search
  - use the `_prev` pointer, which points to the predecessor of a node (O(1)), and back up until hit end of B+/A- grey area

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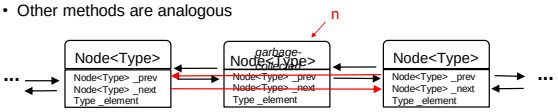
Remove method [For Sorted Doubly Linked List]

- This is *pseudo-code* for a `remove` method for a Sorted Doubly Linked List
  - note dot-notation for variables – a common practice for pseudo-code
  - this is incomplete: does not deal with edge cases (element not found, last in list, etc.)
- Other methods are analogous

```
remove(Type t)
  Node n = search(t)
  set n._prev's _next variable to n._next
  set n._next's _prev variable to n._prev
  //n is now garbage collected
  return n's _element
```



80

Node [For Doubly Linked Lists]

```
public class Node<Type> {
    private Type _element;
    private Node<Type> _next;
    private Node<Type> _prev; // New!

    public Node(Type element) {
        _element=element;
        _next=null;
        _prev = null;
    }

    public void setNext(Node<Type> next) {
        _next=next;
    }

    public Node<Type> getNext() {
        return _next;
    }

    public void setPrev(Node<Type> prev) {
        _prev = prev;
    }

    public Node <Type> getPrev() {
        return _prev;
    }

    /* standard mutator and accessor method
  for    _element are elided.*/
}
```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Lecture Question

What methods do Doubly Linked Lists Nodes have that Singly Linked Lists Nodes do not have?

A. `getNext(), setNext()`

B. `getElement(), setElement()`

C. `getPrev(), setPrev()`

D. `getLocation(), setLocation()`

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[Sorted] Singly Linked vs Doubly Linked

Single

- To look for a node (`search`, `insert`, `delete`) **must** start at the beginning and go to the next node n times → no random access!
- Dynamically grow/shrink
- Can `insert` or `remove` nodes anywhere in the list

Double

- Same functionality as Single
- Has a previous pointer `_prev`
  - for `removeLast`, don't need to loop through entire list to find predecessor
  - don't have to maintain separate `_prev` pointer for `search`
- Traverse in both directions
- Requires more memory/storage (more pointers)

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Linked List Exercises

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How To Build A Node List

- Now that we have a building block, there are a number of methods we can implement to make a higher-level `NodeList` that implements Java's `List` interface (like `ArrayList` does)
  - note: `List` interface is very general…
- Main addition `List` mandates is to support indexing into the `NodeList`. Let's write one of the simpler ones:
  - `get(int i)` method that returns element (`Type`) at that index

`search` Private Helper Method

- First, define a `search` helper method to return node at a particular index
- Want to use this helper method in the class, but don't want to expose found nodes publicly; that would violate encapsulation - make helper `private`
- If a provided index is out of bounds, return `null` (print line is an optional error message)
- Otherwise, iterate through list until node at desired index is reached and return that node

```
public class NodeList<Type> {
    //constructor elided
    private Node<Type> search(int i) {
        if(i < 0 || i >= _size) {
            System.out.println("Invalid index");
            return null;
        }
        Node<Type> curr = _head;
        //for loop stops at i; pointer-chase to i
        for (int counter = 0; counter < i;
                                counter++) {
            curr = curr.getNext();
        }

        return curr;
    }
}
```


`search` Private Helper Method Runtime

```
private Node<Type> search(int i) {
    if (i >= _size || i < 0) {                  // 1 op
        System.out.println("Invalid index");    // 1 op
        return null;                            // 1 op
    }

    Node<Type> curr = _head;                    // 1 op
    for (int counter = 0; counter < i; counter++) {   // n ops
        curr = curr.getNext();                  // 1 op
    }

    return curr;                                // 1 op
}
```

→ `search(int i)` is O(n)

Public Wrapper Method

- Write the publicly accessible wrapper code for the `NodeList`'s `get` method
  - this shows a very common pattern of "thin wrappers" over private code

```
//inside NodeList
public Type get(int i) {
    return this.search(i).getElement();
}
```


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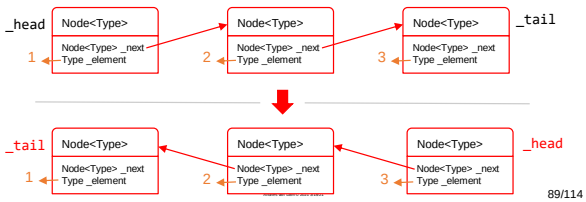
An Exercise
("CS16-Style", common job interview question)

- Write a method that reverses the order of a `MyLinkedList`



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Solution A

- If list is empty or has 1 node, return list
- Otherwise, create a new list of same type as input list
- Iterate through input list, removing first element each time and adding it as first element of new list

```
public MyLinkedList<Type> reverse(MyLinkedList<Type> toReverse) {
    if (toReverse.size() < 2) {
        return toReverse;
    }

    MyLinkedList<Type> newList = new MyLinkedList<Type>();

    int origSize = toReverse.size();

    while (newList.size() < origSize) {
        newList.addFirst(toReverse.removeFirst());
    }

    return newList;
}
```


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Solution B (1/2)

- Is there a better way?
- First algorithm reversed in O(n) time
  - but it wasn't "*in-place*" – (had to create a new list)
- Can write a method *within* `MyLinkedList` that reverses itself without creating new nodes
  - still O(n) but in-place and therefore more efficient

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Solution B (2/2)

- Keep track of previous, current, and next node
- While current node isn't `null`, iterate through nodes, resetting node pointers in reverse
- In doing so, must be careful not to delete any references further on in the list
- Finally, set the `_head` pointer to what had been the last node (held in the `prev` variable)
- If the list is empty `curr` will be `null`, so the loop will never begin and `_head` will continue to point to `null`

```
public void reverse() {
    Node<Type> prev = null;
    Node<Type> curr = _head;
    Node<Type> next = null;
    _tail = _head; //set tail to head

    while (curr != null) {
        next = curr.getNext();
        curr.setNext(prev);
        prev = curr;
        curr = next;
    }

    _head = prev;
}
```


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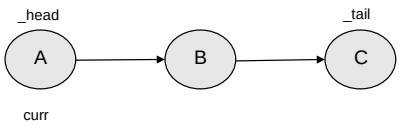
Solution B Walkthrough (1/15)



next = null

prev = null

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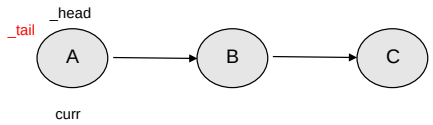
Solution B Walkthrough (2/15)



next = null
prev = null

```
_tail = _head;
```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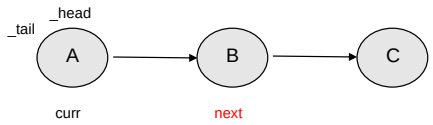
Solution B Walkthrough (3/15)



prev = null

```
while(curr!=null){
      next = curr.getNext();
      curr.setNext(prev);
      prev = curr;
      curr = next;
}
```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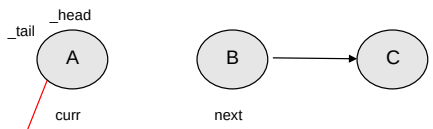
Solution B Walkthrough (4/15)



prev = null

```
while(curr!=null){
      next = curr.getNext();
      curr.setNext(prev);
      prev = curr;
      curr = next;
}
```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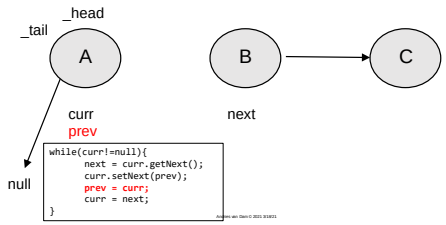
Solution B Walkthrough (5/15)



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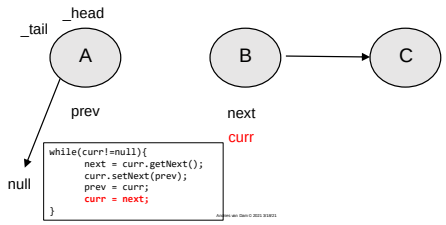
Solution B Walkthrough (6/15)



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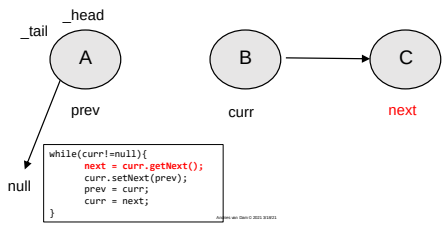
98

Solution B Walkthrough (7/15)



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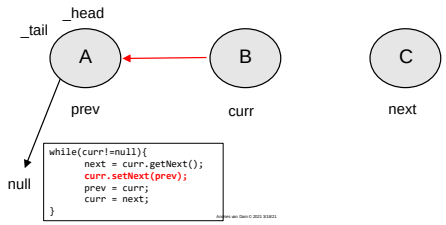
Solution B Walkthrough (8/15)



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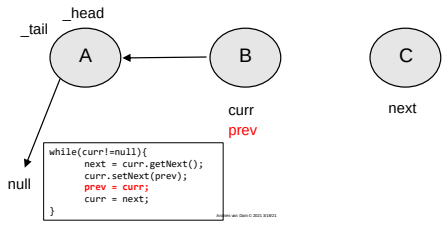
100

Solution B Walkthrough (9/15)



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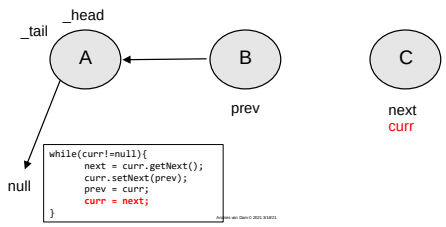
Solution B Walkthrough (10/15)



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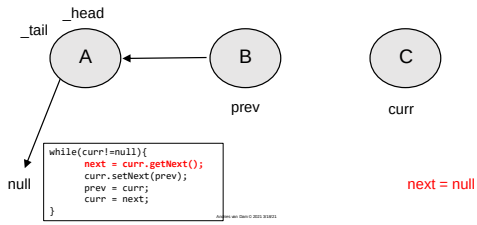
Solution B Walkthrough (11/15)



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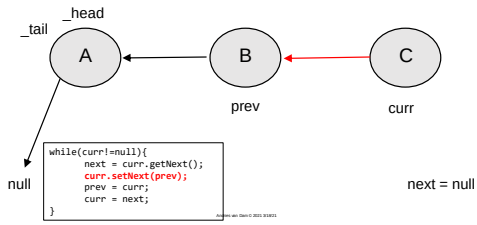
Solution B Walkthrough (12/15)



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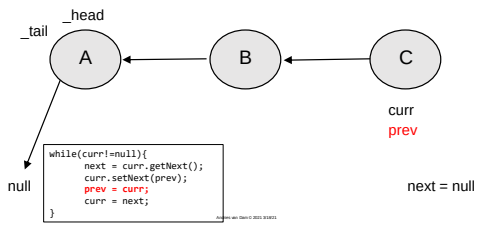
Solution B Walkthrough (13/15)



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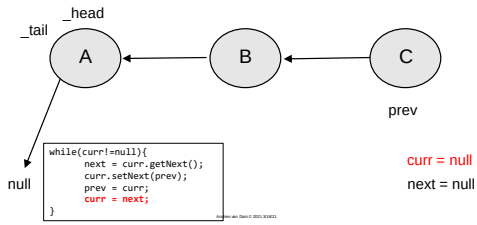
Solution B Walkthrough (14/15)



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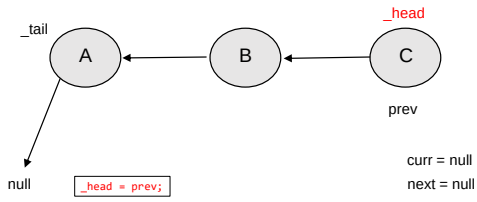
Solution B Walkthrough (15/15)



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Announcements

- DoodleJump late deadline Friday 3/19!
- Tetris is out!
  - Early hand-in Monday 3/29
  - On-time hand-in Wednesday 3/31
  - Late hand-in Friday 4/2
- Reminder: you cannot use your late days on the Final Project, so the last project to apply them to is Tetris

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IT in the News

ft. Socially Responsible Computing!



Labor in the Tech Industry

- Vast disparity in working conditions of highly paid employees (ex. software engineers) and underpaid, overworked employees (ex. assembly workers)

Workers at the Google office in Dublin, Ireland

Workers mining cobalt for lithium battery-powered smartphones in DRC, Africa

Content Warning: Suicide

- **"Foxconn Suicides"** → series of suicides linked to low pay and meticulous, grueling workplace conditions at Foxconn electronics manufacturing plant in Shenzhen, China
- Foxconn is a **major manufacturer of Apple products**

Suicide Nets at Foxconn factory
Source: Wall Street Journal

Labor in the Tech Industry

Gig economy + subcontracting → tech companies avoid recognizing workers as employees

- Child labor in DRC cobalt mines
  - Tech companies filed to have the suit dismissed, arguing they are **not responsible**
  - Since they don't own cobalt mines and use **intermediary suppliers**, specific sites cannot be identified as sources
- Proposition 22
  - 2020 CA initiative permitting companies to treat ride-share and delivery drivers as **independent contractors,** not employees
  - 5 major gig companies spent over **$200 million** to pass Prop 22!
    - why: *employees* are entitled to fair wages and labor protections; *contractors* are not → Uber, Lyft etc. save $$$
- Content Moderation
  - Facebook **outsources** content moderation to India, Philippines

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"The activity of content moderation just doesn't fit into **Silicon Valley's self-image**. Certain types of activities are very highly **valued and glamorized**—product innovation, clever marketing, engineering … the nitty-gritty world of content moderation **doesn't fit into that**"

—Paul Barrett, director of NYU's Center for Business and Human Rights

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Labor movements within tech

- Tech industry is hostile towards organized labor
  - Google has fired workers for "organizing other employees", today only 700 out of 260,000 employees of Alphabet are unionized
  - Amazon has fought unionization attempts for years, most recently in **Bessemer, Alabama** where workers are voting on whether to form the **first Amazon union in the U.S.**
- Why Unions?
  - Demands for policies in support for women and people of color have led to changes at tech companies
    - Ex. Employees spoke up against firings of Timnit Gebru and Margaret Mitchell
  - Employees can advocate companies to monitor abusive, racist and sexist content on their platforms
    - Ex. Twitter banned Trump after 350 employees wrote a letter demanding an investigation

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