Lecture 8:
The List Data Structure

Wholeness of the Lesson

The List ADT is one of the most general data types, capable of supporting most needs for storing a collection of objects in memory. Different implementations of this data type provide optimizations for different operations – such as insert, delete, find – that are typically supported by Lists. Lists give expression to the natural tendency of pure intelligence to express itself through a sequential unfoldment.

Outline of Topics

- List ADT, Array Lists and including sort and search
- Linked Lists – singly linked, headers, doubly linked, circular linked
- Lists before and after jse5.0
- The List interface, the AbstractList class, and Iterator
- Four ways of Iterating Through Elements in a List
- `Comparators`

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The LIST Abstract Data Type

- "List" is known as an *abstract data type* (ADT) – consisting of a sequence of objects and operations on them.
- Typical operations:

find(Object o)	returns position of first occurrence
findKth(int pos)	returns element based on index
insert(Object o, int pos)	inserts object into specified position
remove(Object o)	removes object
printList()	outputs all elements
makeEmpty()	empties the List

- Can be implemented in more than one way. Array List is one such implementation.

A Growable Array

- *Arrays Are Very Efficient* Arrays are data structures that provide "random access" to elements – to find the *i*th entry, there is no need to traverse the elements prior to the *i*th in order to locate the *i*th entry.

- *Arrays Inconvenient Because of Fixed Length*. Arrays are inconvenient sometimes because it is necessary to commit to a fixed array size before adding elements. If the number of elements then exceeds the array size, a new larger array must be created to accommodate the new elements, and old elements have to be copied into the new array. There are similar problems involved in removing elements and in inserting elements into a specified position.

- *ArrayList*. A convenient data structure that saves the explicit effort of recopying. Here, all the work required to copy over elements into a new array for insert, remove, and adding operations is encapsulated in the class.

- Example: `MyStringList` in `lesson8.mystringlist` (from lab4)

Array Operations Can Be Included in An Array List's Set of Methods

- We consider two operations: *sorting* and *searching a sorted array*

- There are many sorting algorithms; Java provides a sorting routine as part of its API. We will consider a simple one for illustration.

- `MinSort` uses the following approach to perform sorting an array A of integers.
  - Start by creating a new array B that will hold the final sorted values
  - Find the minimum value in A, remove it from A, and place it in position 0 in B.
  - Place the minimum value of the remaining elements of A in position 1 in array B.
  - Continue placing the minimum value of the remaining elements of A in the next available position in B until A is empty.

MinSort for Arrays

- *In-Place MinSort*. MinSort can be implemented without an auxiliary array. This is done by performing a swap after each min value is found. Here is the code:

```
//arr is given as input
int[] arr;
public void sort(){
    if(arr == null || arr.length <=1) return;
    int len = arr.length;
    for(int i = 0; i < len; ++i){
        //find position of min value from arr[i] to arr[len-1]
        int nextMinPos = minpos(i,len-1);

        //place this min value at position i
        swap(i, nextMinPos);
    }
}


void swap(int i, int j){
    String temp = strArray[i];
    strArray[i] = strArray[j];
    strArray[j] = temp;
}
```

(continued)

Exercise: Include a version of `MinSort` in `MyStringList`. Since `Strings` will be compared instead of `int's`, you will need to use the `compareTo` method.

Inefficiencies of Array List `insert`, `add`, `remove` Operations

- If in using an Array List, the operations `remove`, `insert`, and `add` are used predominantly, performance is not optimal because of repeated resizing and other steps that require array copying. For such purposes, another implementation of "List" is better.

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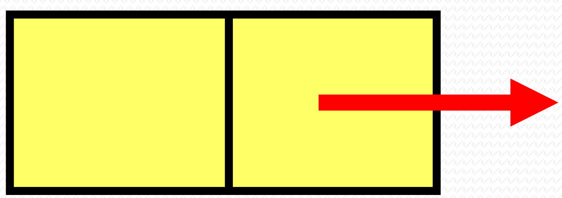
LinkedList Implementation of List: Concept of a Node

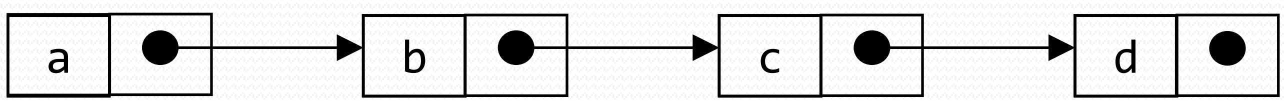
- A LinkedList consists of Nodes. Nodes are structures made up of data and a link to the next Node (which may be null).

data next

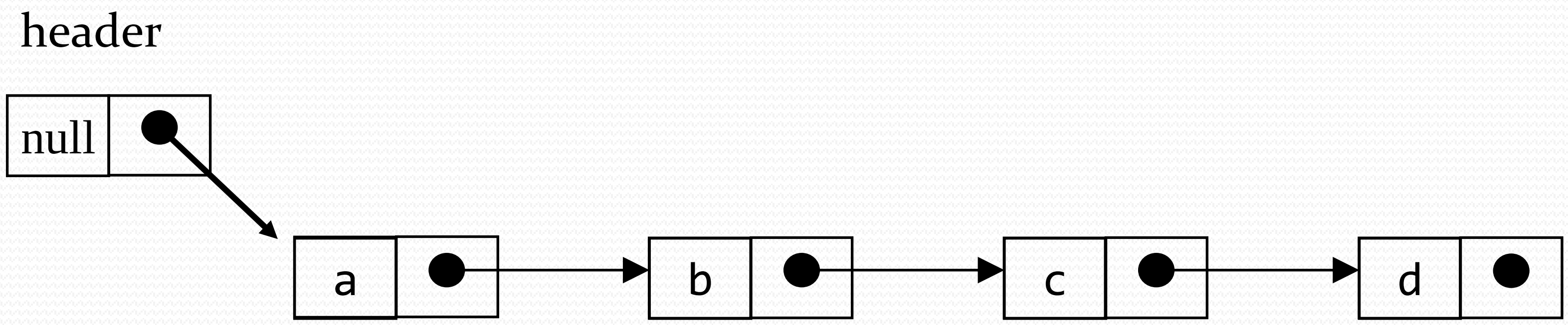
Node:



LinkedList:



Linked Lists with Headers



- A header is a Node that contains no data, can never be removed, and has a link to first Node.

Node Data Structure

```
public class Node {
    String data;
    Node next;

}
```

- In class exercise: build a linkedlist using node data structure.
- See package `lesson8.node`

`LinkedList` Implementation of LIST

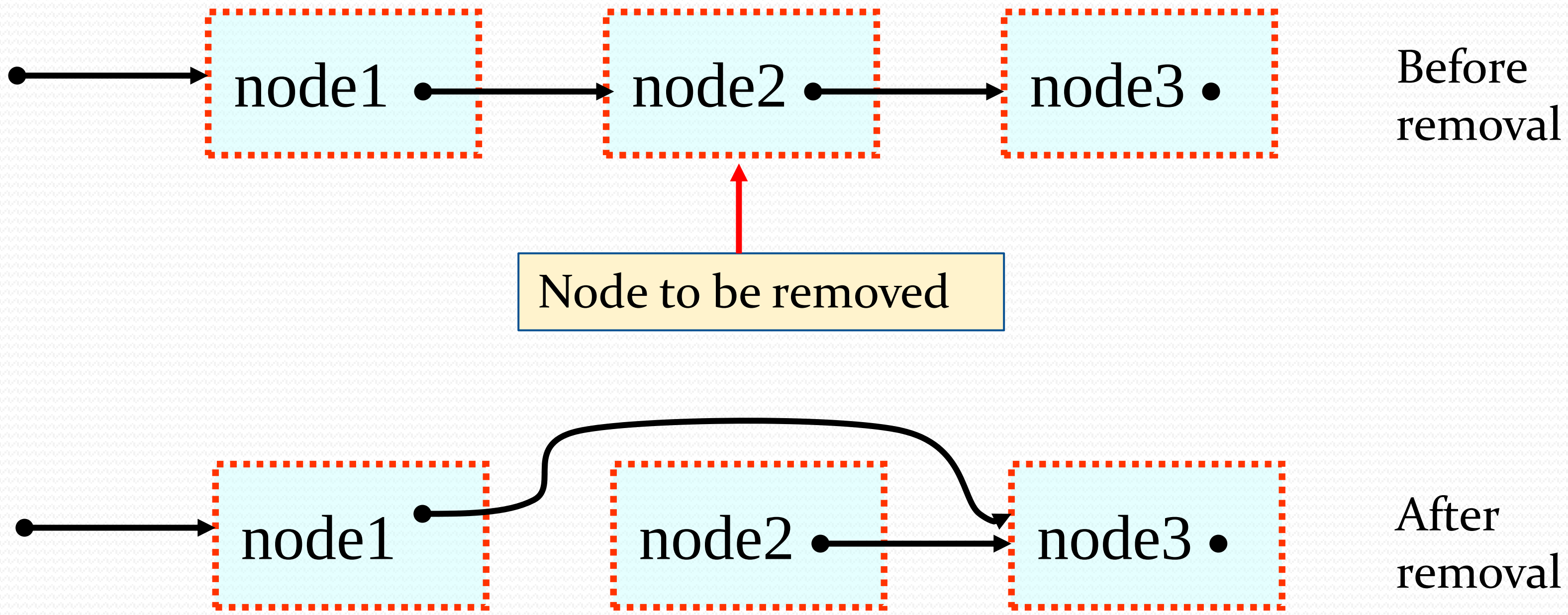
- The Need: Improve performance of *insert, remove, add,* and avoid the cost of resizing incurred by the array implementation.
- ***Operations***
  - *search* requires traversing the Nodes via links, starting at the first Node
  - *insert* requires traversing the Nodes to locate position and adjusting links
  - *remove* requires doing a *find*, and when the object is found, the *previous* object has to be located so that it can be linked to the *next* object

Implementing *search* Operation

- *search* requires traversing the Nodes via links, starting at the first Node
- Demo: `lesson8.singlylinked`

```
boolean search(String s) {
    if(s == null) return false;
    //start node for searches is header.node
    Node current = header.next;
    while(current != null) {
        String t = current.data;
        if(s.equals(t)) {
            return true;
        }
        current = current.next;
    }
    return false;
}
```

Implementing *remove* Operation



Implementing *remove* Operation

- Finding the previous node.
  - Could invoke a routine to go back to the beginning and locate the previous Node
  - remove method could maintain a reference to previous Node

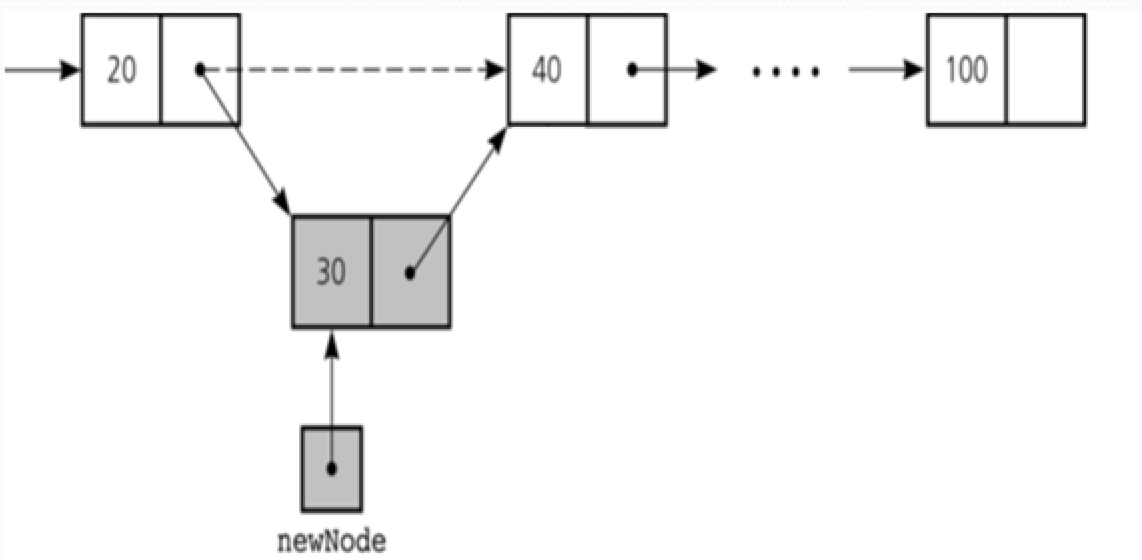
```
void removeNode(String s) {
    if(s == null) return;
    Node next = header.next;
    Node previous = header;

    while(next != null) {
        if(s.equals(next.data)) {
            previous.next = next.next;
            return;
        }
        previous = next;
        next = next.next;
    }
}
```

Exercise: Implementing *Insert* Operation

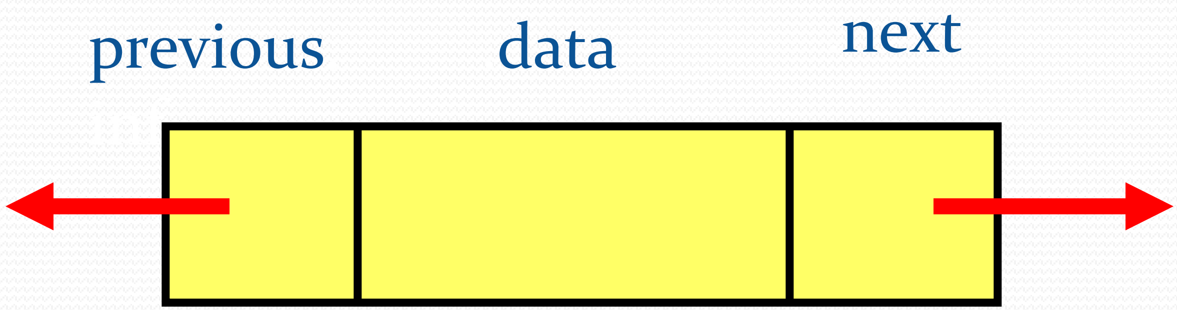
- insert requires traversing the Nodes to locate position and adjusting links
- inserts a new Node contain data so that its position in the list is now pos

```
void insert(String data, int pos)
```



Doubly Linked List

- Each node contains three fields: data stored in the node, a link to the previous node and a link to the next node.



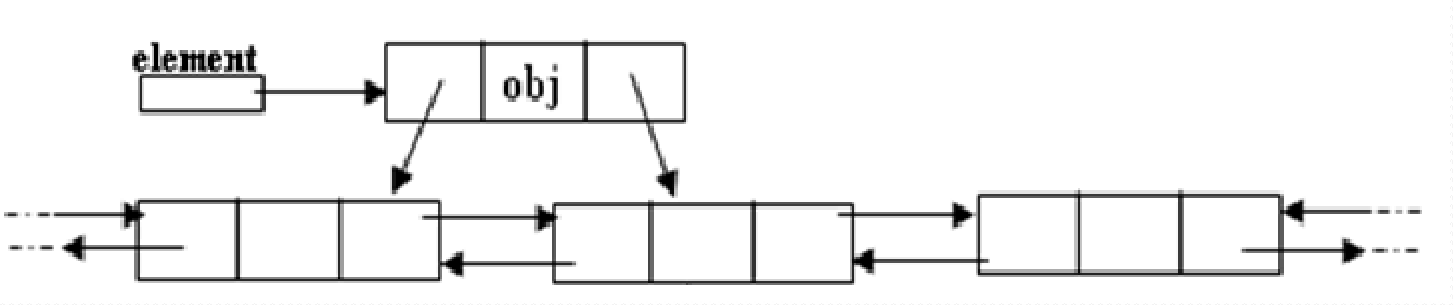
Implementation of Doubly Linked List

```
class Node {
   String value;
   Node next;
   Node previous;
   Node(Node next, Node previous,
          String value){
      this.next = next;
      this.previous = previous;
      this.value = value;
   }
}
```

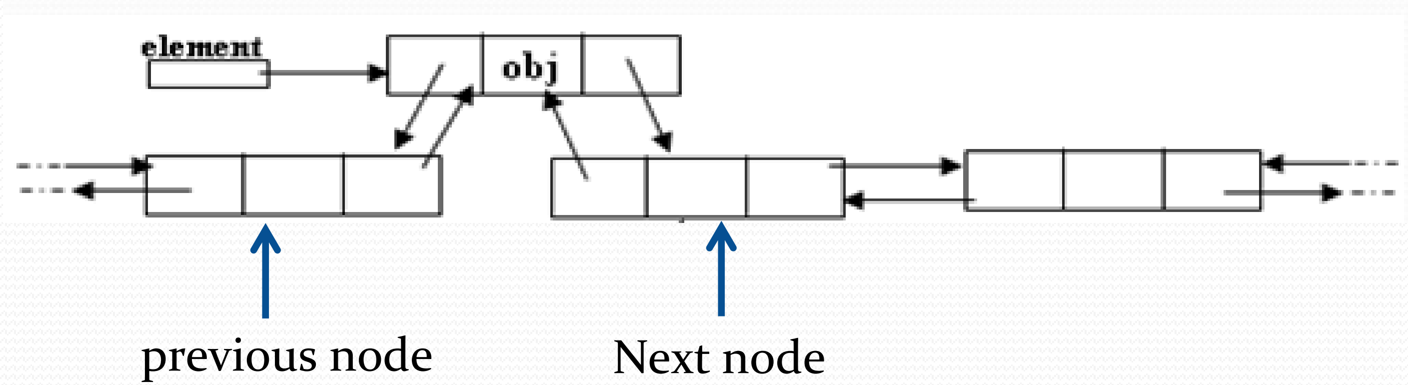
Question: How to implement the `insert` and `remove` operation?

- See Demo (`lesson8.DoublyLinkedList`)

Inserting after a node

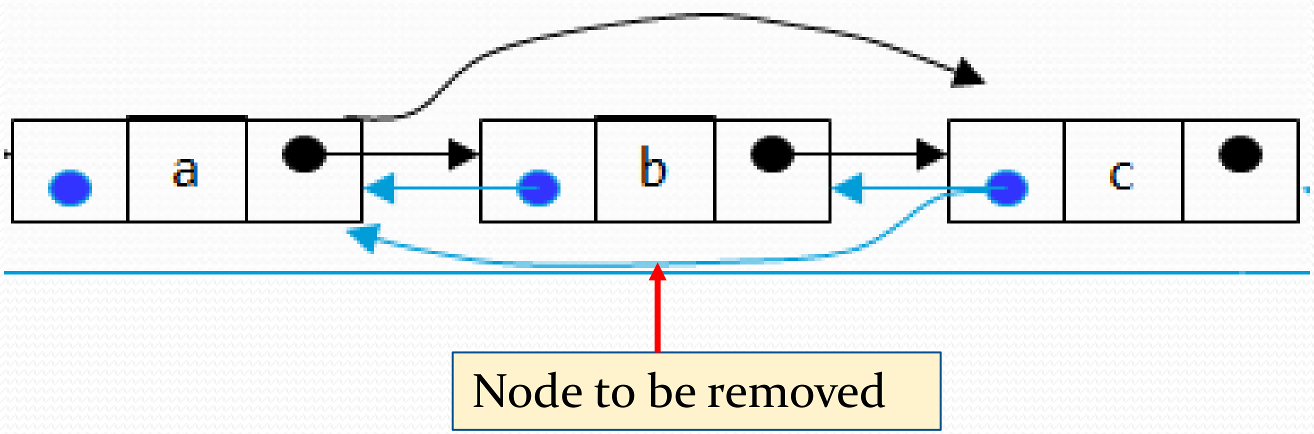


Making next and previous pointer of the new node point to the correct nodes



Adjusting the next and previous pointers of the nodes before and after new node

Deletion after a node



Adjusting the next and previous pointers of the nodes before and after node to be removed

Circular Linked Lists

- In a circular linked list, the last element has a link to the first
- If a header is used, the last element links to the header
- If the LinkedList is doubly linked, and has a header, `header.previous` points to the last element as well
- Making a doubly linked list circular cuts the search time for the operations `insert(Object o, int pos)` and `findKth` in half.

Main Point

The List ADT captures the abstract notion of a “list”; it specifies certain operations that any kind of list should support (for example, *find, findKth, insert, remove*), without specifying the details of implementation.

Different concrete implementations of this abstract data type (such as Array Lists and Linked Lists) meet the contract of the List ADT using different implementation strategies. Likewise, pure awareness is an abstraction of individual awareness; each individual provides a specific, concrete realization of pure consciousness.

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Genericising the Objects Stored in a List

- One difficulty with our examples of Lists – MyStringList and MyStringLinkedList – is that they don’t work if the objects we wish to store are not Strings.
- *Unsatisfactory Solution:* Rewrite the List code for each type as the need arises. E.g. MyEmployeeList, MyIntegerList, MyAccountList. . .
- *A Better Solution:* Could create a List that stores elements of type Object.

Example: MyObjectList

```
public class MyObjectList {
  private final int INITIAL_LENGTH = 4;
  private Object[] objArray;
  private int size;

  public MyObjectList() {
      objArray = new Object[INITIAL_LENGTH];
      size = 0;
  }

  public void add(Object ob){
      if(size == objArray.length) resize();
      objArray[size++] = s;
  }

  . . .
}

//USAGE
MyObjectList list = new MyObjectList();
list.add("Bob");
list.add("Sally");
String name = (String)list.get(1); //downcast necessary
```

Example: MyObjectLinkedList

```
public class MyObjectLinkedList {
  Node header;
  MyObjectLinkedList (){
      header = new Node(null,null, null);
  }
  public void add(Object item){
      Node n = new Node(header.next,header,item);
      if(header.next != null){
          header.next.previous = n;
      }
      header.next = n;

  }
      . . .

  class Node {
      Object value;
      Node next;
      Node previous;
      Node(Node next, Node previous, Object value){
          this.next = next;
          this.previous = previous;
          this.value = value;
      }
  }
}
```

```
//USAGE
MyObjectLinkedList list
      = new MyObjectLinkedList();
list.add("Bob");
list.add("Sally");
String name = (String)list.get(1);
```

Java's Approach (before jdk 1.5)

- Before j2se5.0, Java provided versions of these two kinds of Lists having implementations similar to the above.

- Java's `ArrayList`. This is an array-backed list that accepts any type of object, like MyObjectList above.

  Usage:

```
ArrayList list = new ArrayList();
list.add("Bob");
list.add("Sally");

String name = (String)list.get(1);
```

- Java's `LinkedList`. This is a linked list that accepts any type of object, like MyObjectLinkedList above.

  Usage:

```
LinkedList list = new LinkedList();
list.add("Bob");
list.add("Sally");
String name = (String)list.get(1);
```

Lists and Iteration in JSE5.0

- To do away with the downcasting and support compiler type checking, the Java designers created *parametrized lists* in j2se5.0.

- An example of an undesirable aspect of old-style lists (which parametrized lists fix) is the following:

```
List list2 = new ArrayList();
list2.add("mike");
Integer i = (Integer) list2.get(0);
```

Runtime exception because there is no compiler checking of types in a collection.

- From j2se5.0 on, Lists include a generic parameter. Here are declarations from the Java library:

```
class ArrayList<E> implements List<E> {
    ArrayList<E>() {
            …
    }
}

class LinkedList<E> implements List<E> {
    LinkedList<E>() {
            …
    }
}

interface List<E> {
    void add(E ob);
    E get(int pos);
    boolean remove(E ob);
    int size();

    . . .

}
```

Demo : `lesson8.generic.list`

```
//USAGE
List<String> list = new ArrayList<String>();
list.add("Bob");
list.add("Sally");
String name = list.get(0); //no downcast required

//iterate using for each construct - no
downcasting //needed
for(String s : list) {
  //do something with s
}

//clumsy runtime exceptions are now replaced by
//compiler errors
 List<Integer> list = new ArrayList<Integer>();
      list.add(new Integer(1));
 list.add(new Integer(3));
 //list.add("5"); //compiler won't allow this
```

Restrictions on Parametrized Types

- Rules for Java syntax forbid the creation (but not declaration) of an *array* of parametrized `Lists`:

```
//compiler error
List<String>[] arrayOfLists = new ArrayList<String>[10];

//Workaround: can use an ArrayList instead of an Array:
ArrayList<List<String>> listOfLists =
                        new ArrayList<List<String>>(10);
```

Miscellaneous Facts About Java Lists

- **Inferred Types in JSE 7 and After:**

  When creating an instance of a parametrized type, the parameter can be dropped in the construction step:

  ```
  List<String> list = new ArrayList<>();
  ```

  is the same as:

  ```
  List<String> list = new ArrayList<String>();
  ```

- **Using Lists with Primitives**
  - Lists in Java are designed to aggregate *objects,* not primitives.
  - Autoboxing allows you to use lists with primitives transparently

  ```
  List<Integer> list = new ArrayList<>();
  list.add(5);  //5 converted to Integer type
  ```

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Java's List Interface

- Both ArrayList and LinkedList implement the List interface in the Collections library.
- The operations declared on the List interface are identical to the operations in `ArrayList` and `LinkedList` – here is a partial catalogue:

```
interface List<E> {
    void add(E ob);
    E get(int pos);
    boolean remove(E ob);
    int size();

    . . .

}
```

Programming to the Interface

- Always type your lists as `List` (as implementers of the `List` interface)
  - Supports polymorphism
  - Adds flexibility to your implementation

Example: Start with `ArrayList`:

```
List<String> myList = new ArrayList<>();
myList.add("Bob");
myList.add("Dave");
```

Later, decide to switch to `LinkedList`:

```
List<String> myList = new LinkedList<>(); //one small change
myList.add("Bob");
myList.add("Dave");
```

Using Your List with the Collections API

- There is a `Collections` class in the Java library that has many methods like the ones in `Arrays`.

```
Collections.sort(List list)
```

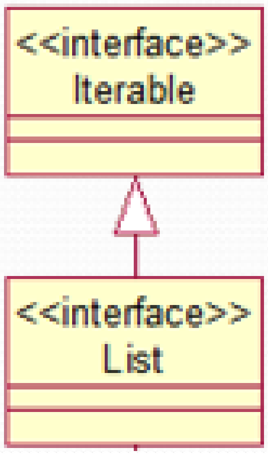
- If you are defining your own list (like `MyStringList`), it is desirable to be able to make use of these methods in `Collections`.
- To use `Collections.sort` with your list, your list must implement the `List` interface

(continued)

- Every implementer of the `List` interface must implement the super-interface `Iterable`, which means that implementers must provide their own iterators.

Java's `Iterable` Interface:

```
interface Iterable {
    Iterator iterator();
}
```



Java's `Iterator` Interface:

`E` is generic type parameter.

```
interface Iterator<E> {
    boolean hasNext();
    E next();
}
```

Sample Implementation of Iterable

Demo: `lesson8.demo.MyStringList`

```
class MyStringList implements Iterable {
      //. .  . .
   public Iterator iterator() {
       return new MyIterator();
   }
   private class MyIterator implements Iterator {
       private int position;
       MyIterator(){
           position = 0;
       }
       public boolean hasNext() {
           return (position < size);
       }
       public Object next() throws IndexOutOfBoundsException {
           if(!hasNext()) throw new IndexOutOfBoundsException();
           return strArray[position++];
       }
       public void reset() {
           position = 0;
       }
   }
```

(continued)

```
public static void main(String[] args){
   MyStringList l = new MyStringList();
   l.add("Bob");
   l.add("Steve");
   l.add("Susan");
   l.add("Mark");
   l.add("Dave");
   Iterator iterator = l.iterator();
   //can explicitly use the iterator
   while(iterator.hasNext()){
      System.out.println(iterator.next());
   }
}
```

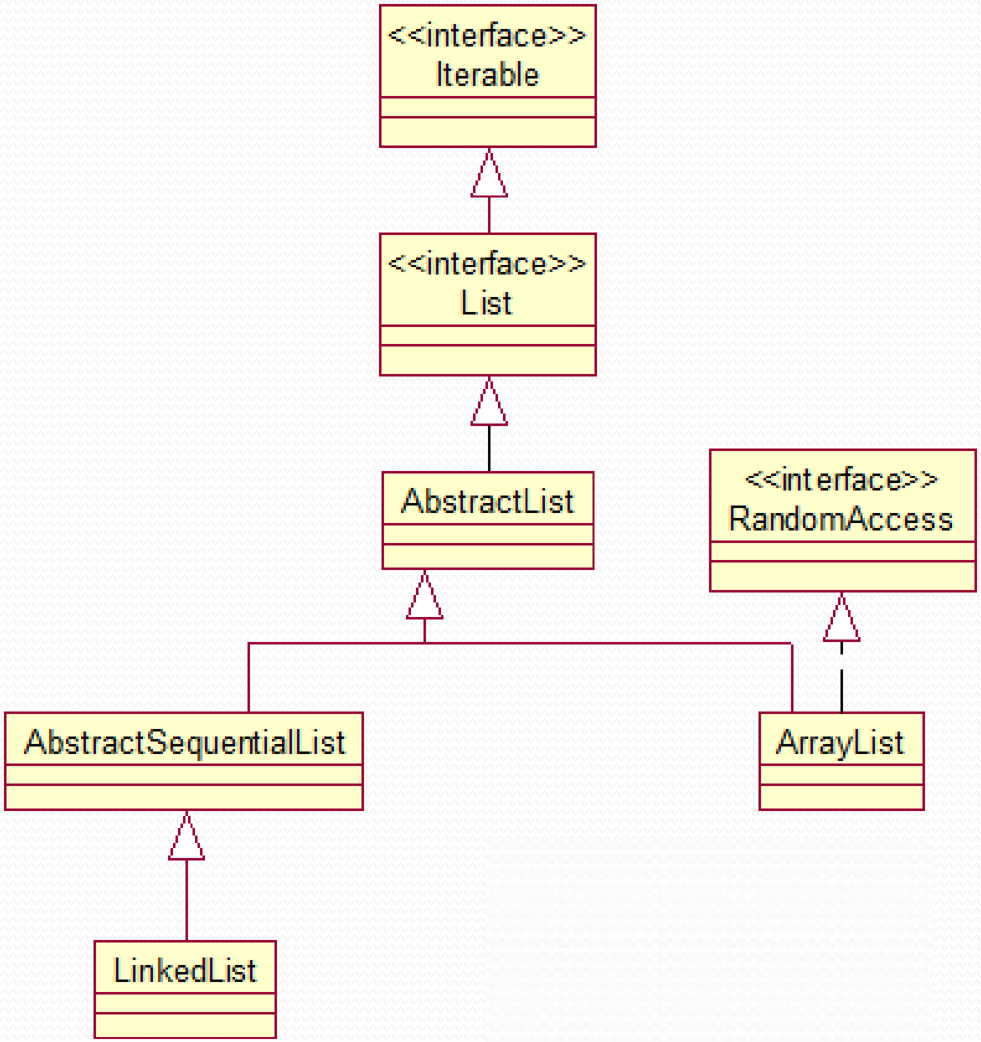
Using `AbstractList` with Your List Class

- In addition to the `iterator` method, implementers of `List` must also implement 14 other abstract `List` methods.
- Instead of implementing all the methods in the `List` interface, you can use default implementations provided by the `AbstractList` class.
- `AbstractList` has
  - One abstract method: `get(int i)`
  - Three methods that need to be overridden: `add, remove, set` (by default each of these throws an `UnsupportedOperationException`).
- *Big advantage.* Using `AbstractList` as a superclass for your list implementations provides you with an implementation of `Iterator`, saving you from the effort of implementing your own.

Example: Extending `AbstractList`

```
//declare your list to extend AbstractList
public class MyStringList extends AbstractList { ...  }

public class Test {
    public static void main(String[] args){
       MyStringList l = new MyStringList();
       l.add("Bob");
       l.add("Steve");
       l.add("Susan");
       l.add("Mark");
       l.add("Dave");
       //uses the implementation provided in AbstractList
       Iterator iterator = l.iterator();
       while(iterator.hasNext()){
          System.out.println(iterator.next());
       }
    }
}
```


<<interface>>
Iterable
<<interface>>
List
AbstractList
<<interface>>
RandomAccess
AbstractSequentialList
ArrayList
LinkedList

Summary on ArrayList and LinkedList

ArrayList	Linked list
Fixed size: Resizing is expensive	Dynamic size
Insertions and Deletions are inefficient: Elements are usually shifted	Insertions and Deletions are efficient: No shifting
Random access i.e., efficient indexing	No random access Not suitable for operations requiring accessing elements by index such as sorting
No memory waste if the array is full or almost full; otherwise may result in much memory waste.	Since memory is allocated dynamically(acc. to our need) there is no waste of memory.

Main Point

An Array List encapsulates the random access behavior of arrays, and incorporates automatic resizing and optionally may include support for sorting and searching. Using a style of sequential access instead, Linked Lists improve performance of insertions and deletions, but at the cost of losing fast element access by index.

Random and sequential access provide analogies for forms of gaining knowledge. Knowledge by way of the intellect is always sequential, requiring steps of logic to arrive at an item of knowledge. Knowing by intuition (*prathibha*) , or by way of *ritam-bhara pragya*, is knowing the truth without steps – a kind of “random access” mode of gaining knowledge.

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Iterating Through Elements in a List

- Demo: `lesson8.traverse.lists`
- First way – Using for loops

```
List<String> list = new ArrayList<>();
……
String next = null;
for(int i = 0; i < list.size(); ++i) {
    next = list.get(i);
    //do something with next
}
```

Iterating Through Elements in a List

- Second way – Using Iterator

```
String next = null;
Iterator<String> iterator = list.iterator();
while(iterator.hasNext()) {
    next = iterator.next();
    //do something
}
```

Iterating Through Elements in a List

- Third way – Using for each construct (the list has to implement `Iterable` in order to use for each construct)

```
//use the for each construct, which uses an
//iterator in the background

for(String str : list) {
    //do something
}
```

Iterating Through Elements in a List

- Fourth way – Using Java 8's New `forEach` Function
- A default method `forEach` was added to the `Iterable` interface. Consequently, any Java library class that implements `Iterable`, as well as any user-defined class that implements `Iterable`, has automatic access to this new method.

  The `forEach` method takes a lambda expression of the form `x -> function(x)` where `function(x)` does not return a value.

- Examples:

```
//Java's List
List<String> javaList
        = new ArrayList<>();
javaList.add("Bob");
javaList.add("Carol");
javaList.add("Steve);

javaList.forEach(
     name ->
       System.out.println(name)
);
//output
Bob
Carol
Steve
```

```
//User-defined list that
//implements Iterable
MyStringList list = new
MyStringList();
list.add("Bob");
list.add("Carol");
list.add("Steve);

list.forEach(
     name ->
       System.out.println(name));

//output
Bob
Carol
Steve
```

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Comparing Objects for Sorting and Searching

- Java supports sorting of many types of objects. To sort a list of objects, it is necessary to have some "ordering" on the objects. For example, there is a natural ordering on numbers and on `Strings`. But what about a list of `Employee` objects?
- In practice, we may want to sort business objects in different ways. An `Employee` list could be sorted by name, salary or hire date.

Employee Data		
Name	Hire Date	Salary
Joe Smith	11/23/2000	50000
Susan Randolph	2/14/2002	60000
Ronald Richards	1/1/2005	70000

- Implementing the `Comparable` interface allows you to sort a list of `Employee`s with reference to one primary field – for instance, you could sort by `name` or by `salary`, but you do not have the option to change this primary field.

- A more flexible interface for such requirements is provided by the **Comparator** interface, whose only method is **compare()**. Like lists, in j2se5.0, `Comparators` are parametrized.

```
public interface Comparator<T> {
    int compare(T o1, T o2);
}
```

- The `compare` method is expected to behave in the following way:

  For objects a and b,
  - compare(a,b) returns a negative number if a is “less than” b
  - compare(a,b) returns a positive number if a is “greater than” b
  - compare(a,b) returns 0 if a “equals” b

`Comparators` and the `compare` Contract

The compare contract for `Comparators`:

It *must* be true that:

- a is “less than” b if and only if b is “greater than” a
- if a is “less than” b and b is “less than” c, then a must be “less than” c.

It *should* also be true that the `Comparator` is *consistent with equals*; in other words:

- `compare(a,b) == 0` if and only if `a.equals(b)`

If a `Comparator` is not consistent with equals, problems can arise when using different container classes. For instance, the `contains` method of a Java `List` uses equals to decide if an object is in a list. However, containers that maintain the order relationship among elements (like `TreeSet` – more on this one later) check whether the output of compare is 0 to implement `contains`.

Example: A Name Comparator

Demo: `lesson8.comparator`

```
// Assumes Employee contains just name and hireDate as
// instance variables
public class NameComparator implements Comparator<Employee> {
     //is this implementation consistent with equals?
    public int compare(Employee e1, Employee e2) {
        return e1.getName().compareTo(e2.getName());
    }
}
public class EmployeeSort {
    public static void main(String[] args) {
        new EmployeeSort();
    }
    public EmployeeSort() {
        Employee[] empArray =
            {new Employee("George", 1996,11,5),
            new Employee("Dave", 2000, 1, 3),
            new Employee("Richard", 2001, 2, 7)};
        List<Employee> empList = Arrays.asList(empArray);
        Comparator<Employee> nameComp = new NameComparator();
        Collections.sort(empList, nameComp);
        System.out.println(empList);
    }
}
public class Employee {
    private String firstName;
    private Date hireDate;
    // . . .
}
```

Question

- How can the `Comparator` in the previous example be made consistent with equals?

Solution

```
public class NameComparator implements
       Comparator<Employee> {
   // consistent with equals
   public int compare(Employee e1, Employee e2) {
      String name1 = e1.getName();
      String name2 = e2.getName();
      Date hireDate1 = e1.getHireDay();
      Date hireDate2 = e2.getHireDay();
      if(name1.compareTo(name2) != 0) {
         return name1.compareTo(name2);
      }
      //in this case, name1.equals(name2) is true
      return hireDate1.compareTo(hireDate2);
   }
}
```

Connecting the Parts of Knowledge With the Wholeness of Knowledge

All knowledge contained in point

1. An implementation of the abstract class AbstractSequentialList in Java (such as a LinkedList) results in a list that has only sequential access to its elements.
2. An implementation of the RandomAccess interface in Java (such as ArrayList and Vector) results in a list that has random access (and therefore, effectively, instantaneous access) to its elements.

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3. **Transcendental Consciousness:** TC is the home of all knowledge. All knowledge has its basis in the unbounded field of pure consciousness.
4. **Wholeness moving within itself**: In Unity Consciousness, when the home of all knowledge has become fully integrated in all phases of life, it is possible to know anything, any particular thing, instantly.