Linked Lists
(POO 2008/2009)

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Chapter Goals

- To learn how to use the linked lists provided in the standard library
- To be able to use iterators to traverse linked lists
- To understand the implementation of linked lists
- To distinguish between abstract and concrete data types

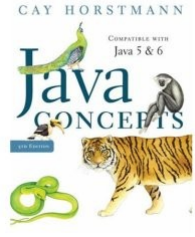
Continued

Chapter Goals

- To know the efficiency of fundamental operations of lists and arrays
- To become familiar with the stack and queue types

Where can I find this chapter?

← Chapter 20

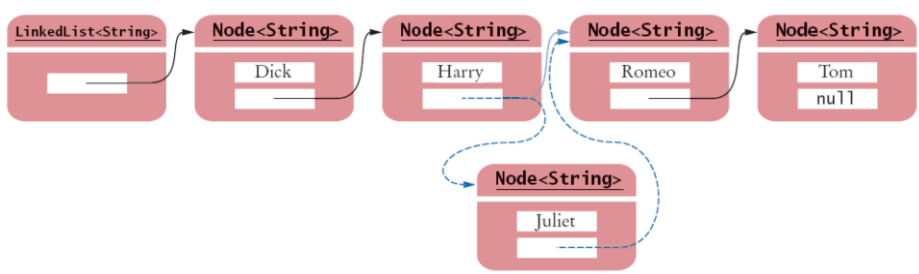


← Chapter 15
(electronic chapter)

Using Linked Lists

- A linked list consists of a number of nodes, each of which has a reference to the next node
- Adding and removing elements in the middle of a linked list is efficient
- Visiting the elements of a linked list in sequential order is efficient
- Random access is not efficient

Inserting an Element into a Linked List



Java's `LinkedList` class

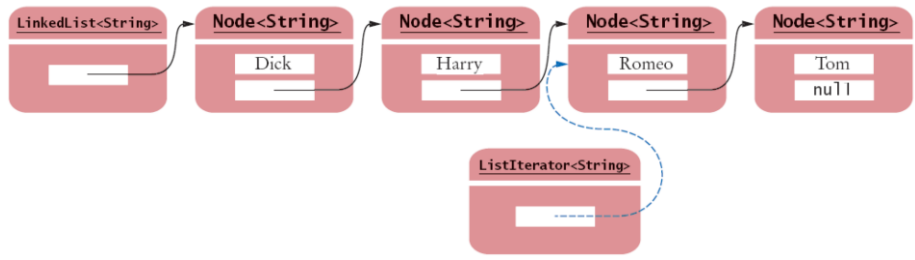
- Generic class
  - Specify type of elements in angle brackets: `LinkedList<Product>`
- Package: `java.util`
- Easy access to first and last elements with methods

```
void addFirst(E obj)
void addLast(E obj)
E getFirst()
E getLast()
E removeFirst()
E removeLast()
```

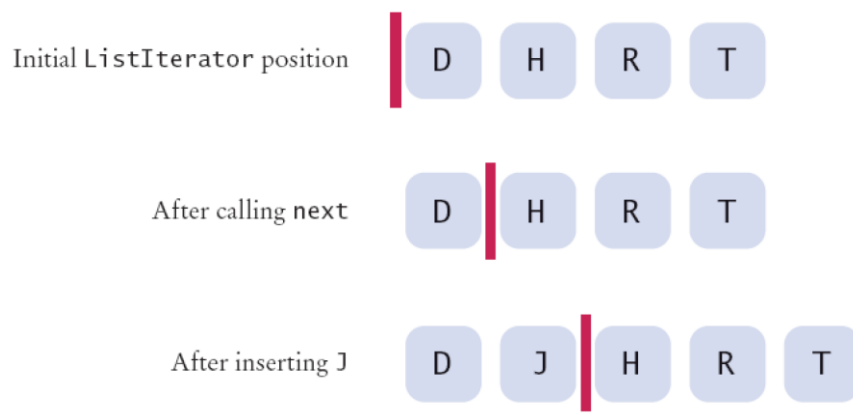
List Iterator

- `ListIterator` type
  - Gives access to elements inside a linked list
  - Encapsulates a position anywhere inside the linked list
  - Protects the linked list while giving access

A List Iterator



A Conceptual View of a List Iterator



List Iterator

- Think of an iterator as pointing between two elements
  - Analogy: like the cursor in a word processor points between two characters
- The `listIterator` method of the `LinkedList` class gets a list iterator

```
LinkedList<String> employeeNames = . . .;
ListIterator<String> iterator = employeeNames.listIterator();
```

List Iterator

- Initially, the iterator points before the first element
- The `next` method moves the iterator

```
iterator.next();
```

- `next` throws a `NoSuchElementException` if you are already past the end of the list
- `hasNext` returns true if there is a next element

```
if (iterator.hasNext())
   iterator.next();
```

List Iterator

- The `next` method returns the element that the iterator is passing

```
while iterator.hasNext()
{
   String name = iterator.next();
   Do something with name
}
```

Continued

List Iterator

- Shorthand:

```
for (String name : employeeNames)
{
   Do something with name
}
```

Behind the scenes, the `for` loop uses an iterator to visit all list elements

List Iterator

- `LinkedList` is a *doubly linked list*
  - Class stores two links:
    - One to the next element, and
    - One to the previous element
- To move the list position backwards, use:
  - `hasPrevious`
  - `previous`

Adding and Removing from a `LinkedList`

- The `add` method:
  - Adds an object after the iterator
  - Moves the iterator position past the new element

```
iterator.add("Juliet");
```

Adding and Removing from a `LinkedList`

- The `remove` method
  - Removes and
  - Returns the object that was returned by the last call to `next` or `previous`

```
//Remove all names that fulfill a certain condition
while (iterator.hasNext())
{
   String name = iterator.next();
   if (name fulfills condition)
      iterator.remove();
}
```

Continued

Adding and Removing from a `LinkedList`

- Be careful when calling `remove`:
  - It can be called only once after calling `next` or `previous`
  - You cannot call it immediately after a call to `add`
  - If you call it improperly, it throws an `IllegalStateException`

Sample Program

- `ListTester` is a sample program that
  - Inserts strings into a list
  - Iterates through the list, adding and removing elements
  - Prints the list

File `ListTester.java`

```
01: import java.util.LinkedList;
02: import java.util.ListIterator;
03:
04: /**
05:    A program that demonstrates the LinkedList class
06: */
07: public class ListTester
08: {
09:    public static void main(String[] args)
10:    {
11:       LinkedList<String> staff = new LinkedList<String>();
12:       staff.addLast("Dick");
13:       staff.addLast("Harry");
14:       staff.addLast("Romeo");
15:       staff.addLast("Tom");
16:
17:       // | in the comments indicates the iterator position
18:
```

Continued

File ListTester.java

```
19:     ListIterator<String> iterator
20:           = staff.listIterator(); // |DHRT
21:     iterator.next(); // D|HRT
22:     iterator.next(); // DH|RT
23:
24:     // Add more elements after second element
25:
26:     iterator.add("Juliet"); // DHJ|RT
27:     iterator.add("Nina"); // DHJN|RT
28:
29:     iterator.next(); // DHJNR|T
30:
31:     // Remove last traversed element
32:
33:     iterator.remove(); // DHJN|T
34:
```

Continued

File ListTester.java

```
35:     // Print all elements
36:
37:     for (String name : staff)
38:        System.out.println(name);
39:  }
40: }
```

File `ListTester.java`

- Output:

```
Dick
Harry
Juliet
Nina
Tom
```

Implementing Linked Lists

- Previous section: Java's `LinkedList` class
- Now, we will look at the implementation of a simplified version of this class
- It will show you how the list operations manipulate the links as the list is modified

Continued

Implementing Linked Lists

- To keep it simple, we will implement a singly linked list
  - Class will supply direct access only to the first list element, not the last one
- Our list will not use a type parameter
  - Store raw `Object` values and insert casts when retrieving them

Implementing Linked Lists

- `Node`: stores an object and a reference to the next node
- Methods of linked list class and iterator class have frequent access to the Node instance variables

Continued

Implementing Linked Lists

- To make it easier to use:
  - We do not make the instance variables private
  - We make `Node` a private inner class of `LinkedList`
  - It is safe to leave the instance variables public
    - None of the list methods returns a `Node` object

Implementing Linked Lists

```
public class LinkedList
{
   . . .
   private class Node
   {
      public Object data;
      public Node next;
   }
}
```

Implementing Linked Lists

- `LinkedList` class
  - Holds a reference `first` to the first node
  - Has a method to get the first element

Implementing Linked Lists

```
public class LinkedList
{
   private Node first;
 . . .
   public LinkedList()
   {
      first = null;
   }

   public Object getFirst()
   {
      if (first == null)
         throw new NoSuchElementException();
      return first.data;
   }
}
```

Adding a New First Element

- When a new node is added to the list
  - It becomes the head of the list
  - The old list head becomes its next node

Adding a New First Element

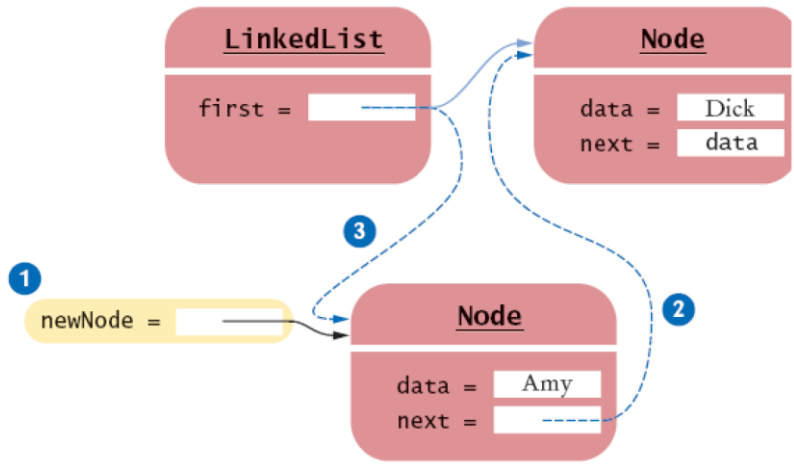
- The `addFirst` method

```
public class LinkedList
{
   . . .
   public void addFirst(Object obj)
   {
      Node newNode = new Node();          1

      newNode.data = obj;
      newNode.next = first;               2

      first = newNode;                    3
   }
   . . .
}
```

Adding a Node to the Head of a Linked List



Removing the First Element

- When the first element is removed
  - The data of the first node are saved and later returned as the method result
  - The successor of the first node becomes the first node of the shorter list
  - The old node will be garbage collected when there are no further references to it

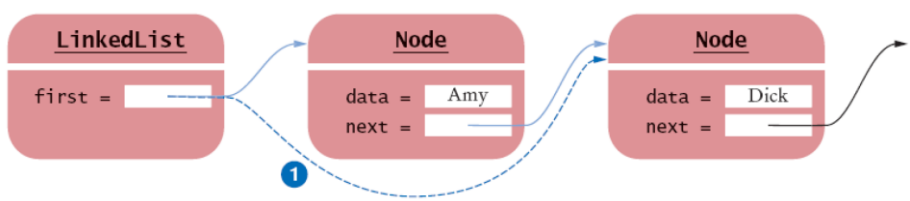
Removing the First Element

- The `removeFirst` method

```
public class LinkedList
{
   . . .
   public Object removeFirst()
   {
      if (first == null)
         throw new NoSuchElementException();
      Object obj = first.data;

      first = first.next;          1
      return obj;
   }
   . . .
}
```

Removing the First Node from a Linked List



Linked List Iterator

- We define `LinkedListIterator`: private inner class of `LinkedList`
- Implements a simplified `ListIterator` interface
- Has access to the `first` field and private `Node` class
- Clients of `LinkedList` don't actually know the name of the iterator class
  - They only know it is a class that implements the `ListIterator` interface

`LinkedListIterator`

- The `LinkListIterator` class

```
public class LinkedList
{
   . . .
   public ListIterator listIterator()
   {
      return new LinkedListIterator();
   }
   private class LinkedListIterator implements ListIterator
   {
      public LinkedListIterator()
      {
         position = null;
         previous = null;
      }
```

Continued

LinkedListIterator

```
    . . .
    private Node position;
    private Node previous;
  }
  . . .
}
```

The Linked List Iterator's `next` method

- `position`: reference to the last visited node
- Also, store a reference to the last reference before that
- `next` method: `position` reference is advanced to `position.next`
- Old position is remembered in `previous`
- If the iterator points before the first element of the list, then the old `position` is `null` and `position` must be set to `first`

The Linked List Iterator's `next` method

```
public Object next()
{
   if (!hasNext())
      throw new NoSuchElementException();
   previous = position; // Remember for remove
   if (position == null)
      position = first;
   else
      position = position.next;
   return position.data;
}
```

The Linked List Iterator's `hasNext` Method

- The `next` method should only be called when the iterator is not at the end of the list
- The iterator is at the end
  - if the list is empty (`first == null`)
  - if there is no element after the current position (`position.next == null`)

The Linked List Iterator's `hasNext` Method

```
private class LinkedListIterator implements ListIterator
{
   . . .
   public boolean hasNext()
   {
      if (position == null)
         return first != null;
      else
         return position.next != null;
   }
   . . .
}
```

The Linked List Iterator's `remove` method

- If the element to be removed is the first element, call `removeFirst`
- Otherwise, the node preceding the element to be removed needs to have its next reference updated to skip the removed element

Continued

The Linked List Iterator's `remove` Method

- If the `previous` reference equals `position`:
  - this call does not immediately follow a call to next
  - throw an `IllegalArgumentException`
  - It is illegal to call `remove` twice in a row
  - `remove` sets the `previous` reference to `position`

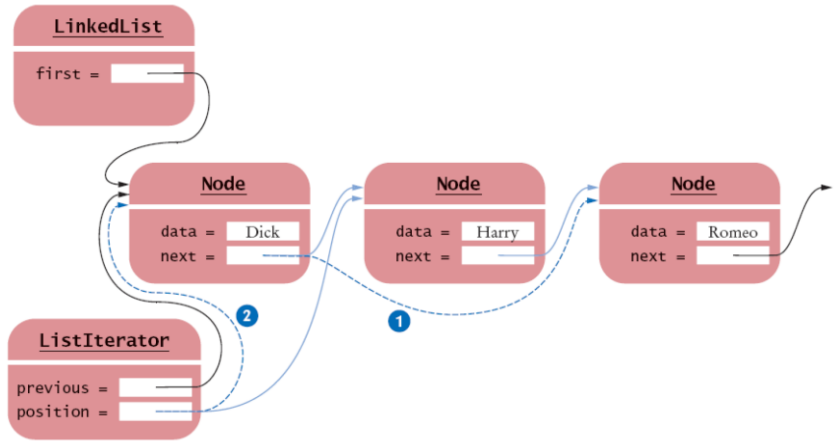
The Linked List Iterator's `remove` Method

```
public void remove()
{
   if (previous == position)
      throw new IllegalStateException();
   if (position == first)
   {
      removeFirst();
   }
   else
   {
      previous.next = position.next;
   }
   position = previous;
}
```

1

2

Removing a Node From the Middle of a Linked List



The Linked List Iterator's `set` Method

- Changes the data stored in the previously visited element
- The `set` method

```
public void set(Object obj)
{
   if (position == null)
      throw new NoSuchElementException();
   position.data = obj;
}
```

The Linked List Iterator's `add` Method

- The most complex operation is the addition of a node
- `add` inserts the new node after the current position
- Sets the successor of the new node to the successor of the current position

The Linked List Iterator's `add` Method

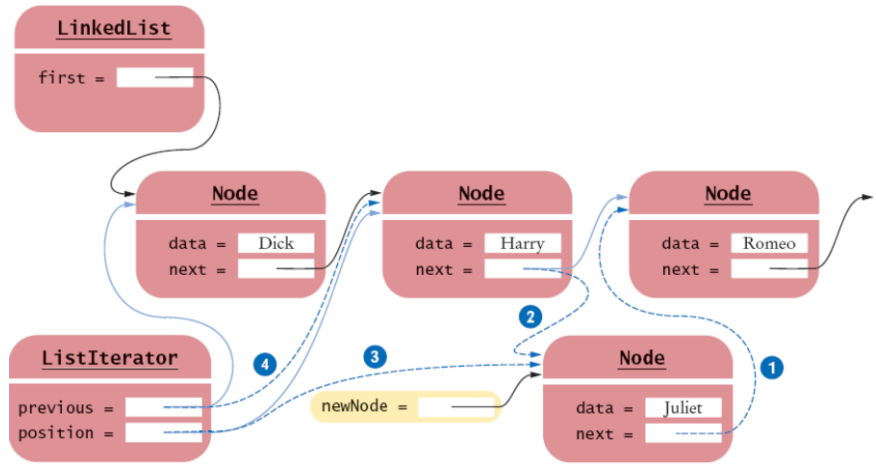
```
public void add(Object obj)
{
   if (position == null)
   {
      addFirst(obj);
      position = first;
   }
   else
   {
      Node newNode = new Node();
      newNode.data = obj;                    1

      newNode.next = position.next;          2

      position.next = newNode;

      position = newNode;                    3
   }
   previous = position;                      4
}
```

Adding a Node to the Middle of a Linked List



File `LinkedList.java`

```
001: import java.util.NoSuchElementException;
002:
003: /**
004:    A linked list is a sequence of nodes with efficient
005:    element insertion and removal. This class
006:    contains a subset of the methods of the standard
007:    java.util.LinkedList class.
008: */
009: public class LinkedList
010: {
011:    /**
012:       Constructs an empty linked list.
013:    */
014:    public LinkedList()
015:    {
016:       first = null;
017:    }
018:
```

Continued

File LinkedList.java

```
019:  /**
020:     Returns the first element in the linked list.
021:     @return the first element in the linked list
022:  */
023:  public Object getFirst()
024:  {
025:     if (first == null)
026:        throw new NoSuchElementException();
027:     return first.data;
028:  }
029:
030:  /**
031:     Removes the first element in the linked list.
032:     @return the removed element
033:  */
034:  public Object removeFirst()
035:  {
```

Continued

File LinkedList.java

```
036:     if (first == null)
037:        throw new NoSuchElementException();
038:     Object element = first.data;
039:     first = first.next;
040:     return element;
041:  }
042:
043:  /**
044:     Adds an element to the front of the linked list.
045:     @param element the element to add
046:  */
047:  public void addFirst(Object element)
048:  {
049:     Node newNode = new Node();
050:     newNode.data = element;
051:     newNode.next = first;
052:     first = newNode;
053:  }
054:
```

Continued

File LinkedList.java

```
055:   /**
056:      Returns an iterator for iterating through this list.
057:      @return an iterator for iterating through this list
058:   */
059:   public ListIterator listIterator()
060:   {
061:      return new LinkedListIterator();
062:   }
063:
064:   private Node first;
065:
066:   private class Node
067:   {
068:      public Object data;
069:      public Node next;
070:   }
071:
```

Continued

File LinkedList.java

```
072:   private class LinkedListIterator implements ListIterator
073:   {
074:      /**
075:         Constructs an iterator that points to the front
076:         of the linked list.
077:      */
078:      public LinkedListIterator()
079:      {
080:         position = null;
081:         previous = null;
082:      }
083:
084:      /**
085:         Moves the iterator past the next element.
086:         @return the traversed element
087:      */
```

Continued

File LinkedList.java

```
088:    public Object next()
089:    {
090:       if (!hasNext())
091:          throw new NoSuchElementException();
092:       previous = position; // Remember for remove
093:
094:       if (position == null)
095:          position = first;
096:       else
097:          position = position.next;
098:
099:       return position.data;
100:    }
101:
102:    /**
103:       Tests if there is an element after the iterator
104:       position.
```

Continued

File LinkedList.java

```
105:       @return true if there is an element after the
           // iterator
106:       position
107:    */
108:    public boolean hasNext()
109:    {
110:       if (position == null)
111:          return first != null;
112:       else
113:          return position.next != null;
114:    }
115:
116:    /**
117:       Adds an element before the iterator position
118:       and moves the iterator past the inserted element.
119:       @param element the element to add
120:    */
```

Continued

File LinkedList.java

```
121:    public void add(Object element)
122:    {
123:       if (position == null)
124:       {
125:          addFirst(element);
126:          position = first;
127:       }
128:       else
129:       {
130:          Node newNode = new Node();
131:          newNode.data = element;
132:          newNode.next = position.next;
133:          position.next = newNode;
134:          position = newNode;
135:       }
136:       previous = position;
137:    }
138:
```

Continued

File LinkedList.java

```
139:    /**
140:       Removes the last traversed element. This method may
141:       only be called after a call to the next() method.
142:    */
143:    public void remove()
144:    {
145:       if (previous == position)
146:          throw new IllegalStateException();
147:
148:       if (position == first)
149:       {
150:          removeFirst();
151:       }
152:       else
153:       {
154:          previous.next = position.next;
155:       }
```

Continued

File LinkedList.java

```
156:          position = previous;
157:       }
158:
159:       /**
160:          Sets the last traversed element to a different
161:          value.
162:          @param element the element to set
163:       */
164:       public void set(Object element)
165:       {
166:          if (position == null)
167:             throw new NoSuchElementException();
168:          position.data = element;
169:       }
170:
171:       private Node position;
172:       private Node previous;
173:    }
174: }
```

File ListIterator.java

```
01: /**
02:    A list iterator allows access of a position in a linked list.
03:    This interface contains a subset of the methods of the
04:    standard java.util.ListIterator interface. The methods for
05:    backward traversal are not included.
06: */
07: public interface ListIterator
08: {
09:    /**
10:       Moves the iterator past the next element.
11:       @return the traversed element
12:    */
13:    Object next();
14:
15:    /**
16:       Tests if there is an element after the iterator
17:       position.
```

Continued

File ListIterator.java

```
18:    @return true if there is an element after the iterator
19:    position
20:  */
21:  boolean hasNext();
22:
23:  /**
24:    Adds an element before the iterator position
25:    and moves the iterator past the inserted element.
26:    @param element the element to add
27:  */
28:  void add(Object element);
29:
30:  /**
31:    Removes the last traversed element. This method may
32:    only be called after a call to the next() method.
33:  */
```

Continued

File ListIterator.java

```
34:  void remove();
35:
36:  /**
37:    Sets the last traversed element to a different
38:    value.
39:    @param element the element to set
40:  */
41:  void set(Object element);
42: }
```

Efficiency of Operations for Arrays and Lists

- Adding or removing an element (List)
  - A fixed number of node references need to be modified to add or remove a node, regardless of the size of the list
  - In big-Oh notation: $O(1)$
- Adding or removing an element (Array)
  - On average $n/2$ elements need to be moved
  - In big-Oh notation: $O(n)$

Efficiency of Operations for Arrays and Lists

Operation	Array	List
Random Access	$O(1)$	$O(n)$
Linear Traversal Step	$O(1)$	$O(1)$
Add/Remove an Element	$O(n)$	$O(1)$