An Introduction to Data Structures

Advanced Programming

ICOM 4015

Lecture 17

Reading: Java Concepts Chapter 20

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

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

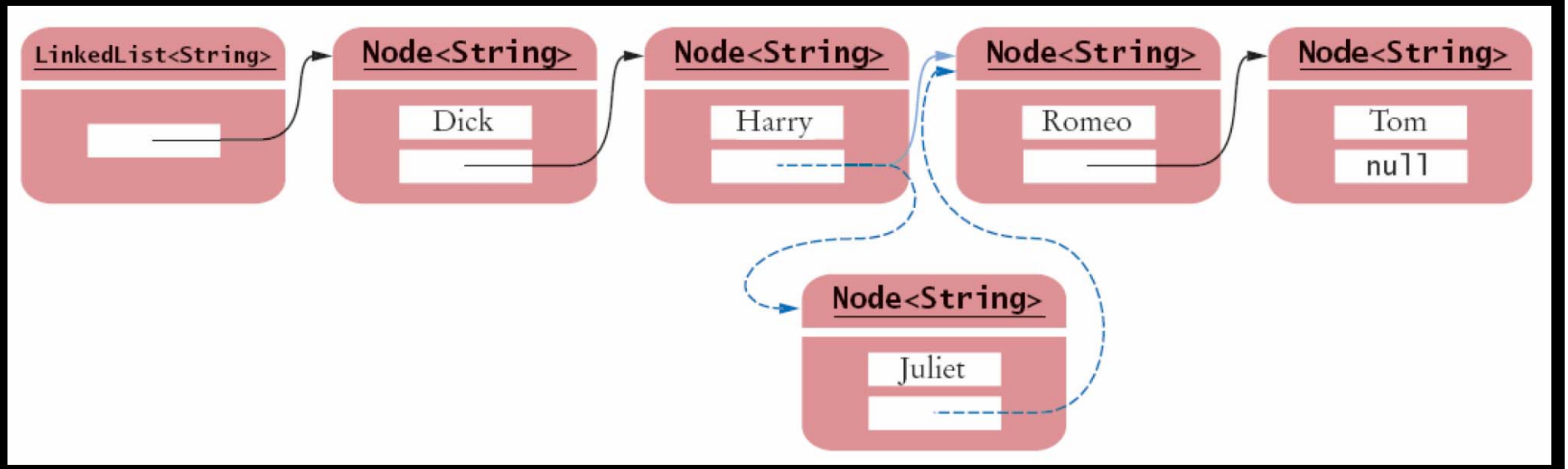


Figure 1:
Inserting an Element into a Linked List

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

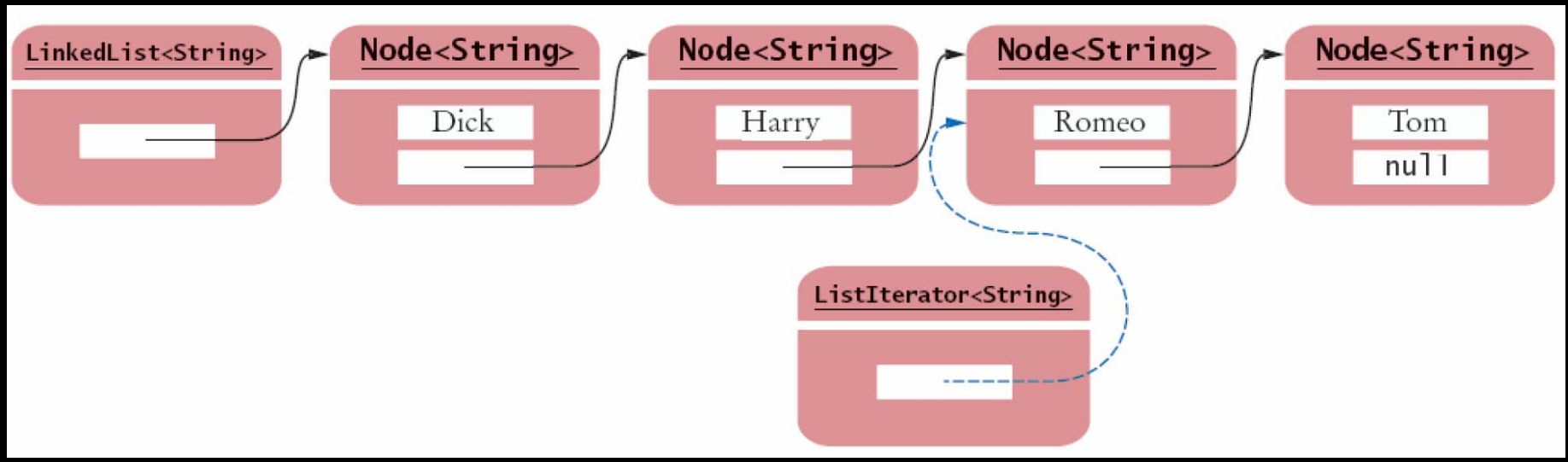


Figure 2:
A List Iterator

A Conceptual View of a List Iterator

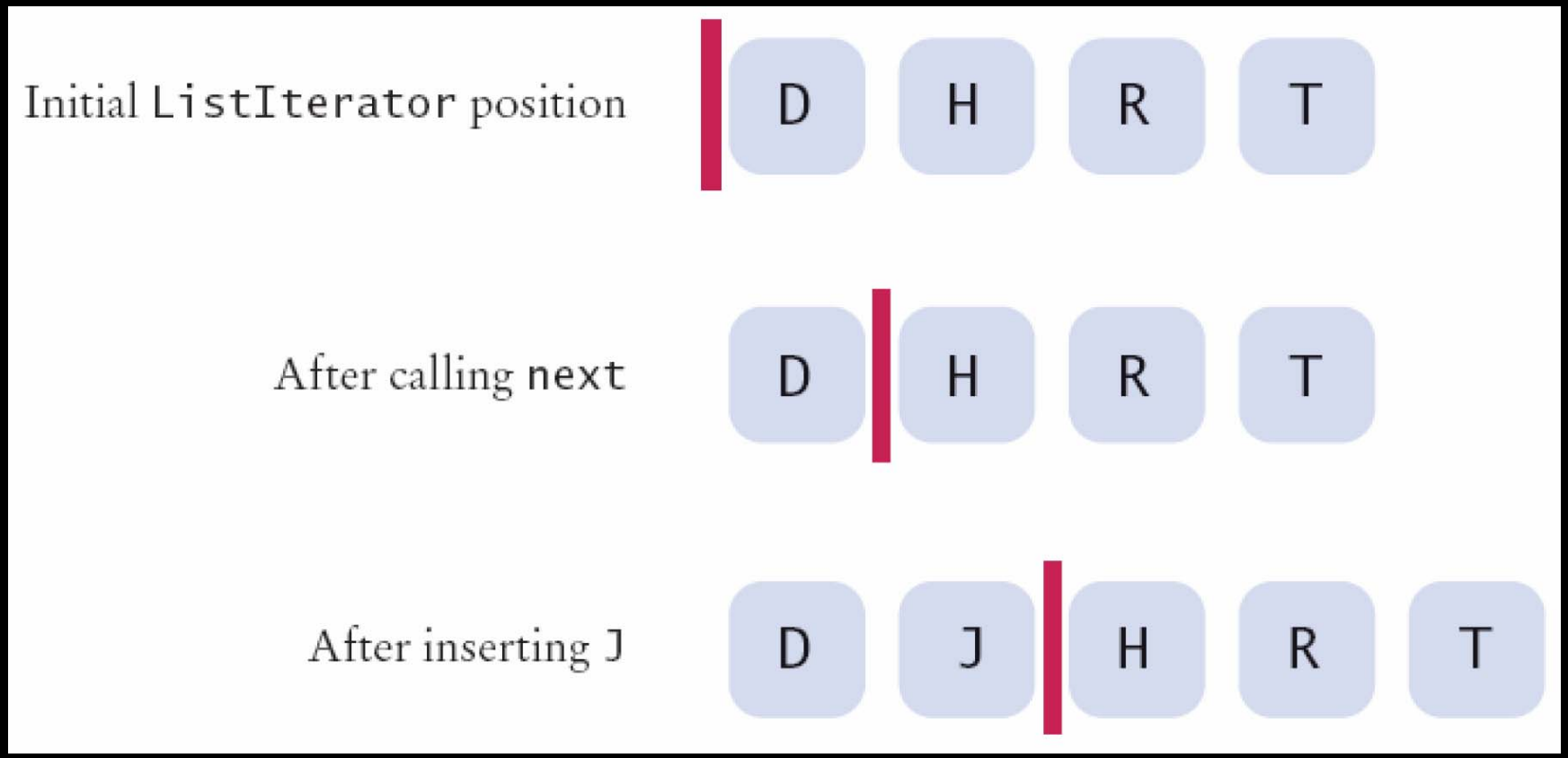


Figure 3:
A Conceptual View of a List Iterator

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
```

Self Test

1. Do linked lists take more storage space than arrays of the same size?
2. Why don't we need iterators with arrays?

Answers

1. Yes, for two reasons. You need to store the node references, and each node is a separate object. (There is a fixed overhead to store each object in the virtual machine.)
2. An integer index can be used to access any array location.

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

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();
      newNode.data = obj; newNode.next = first;

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

Adding a Node to the Head of a Linked List

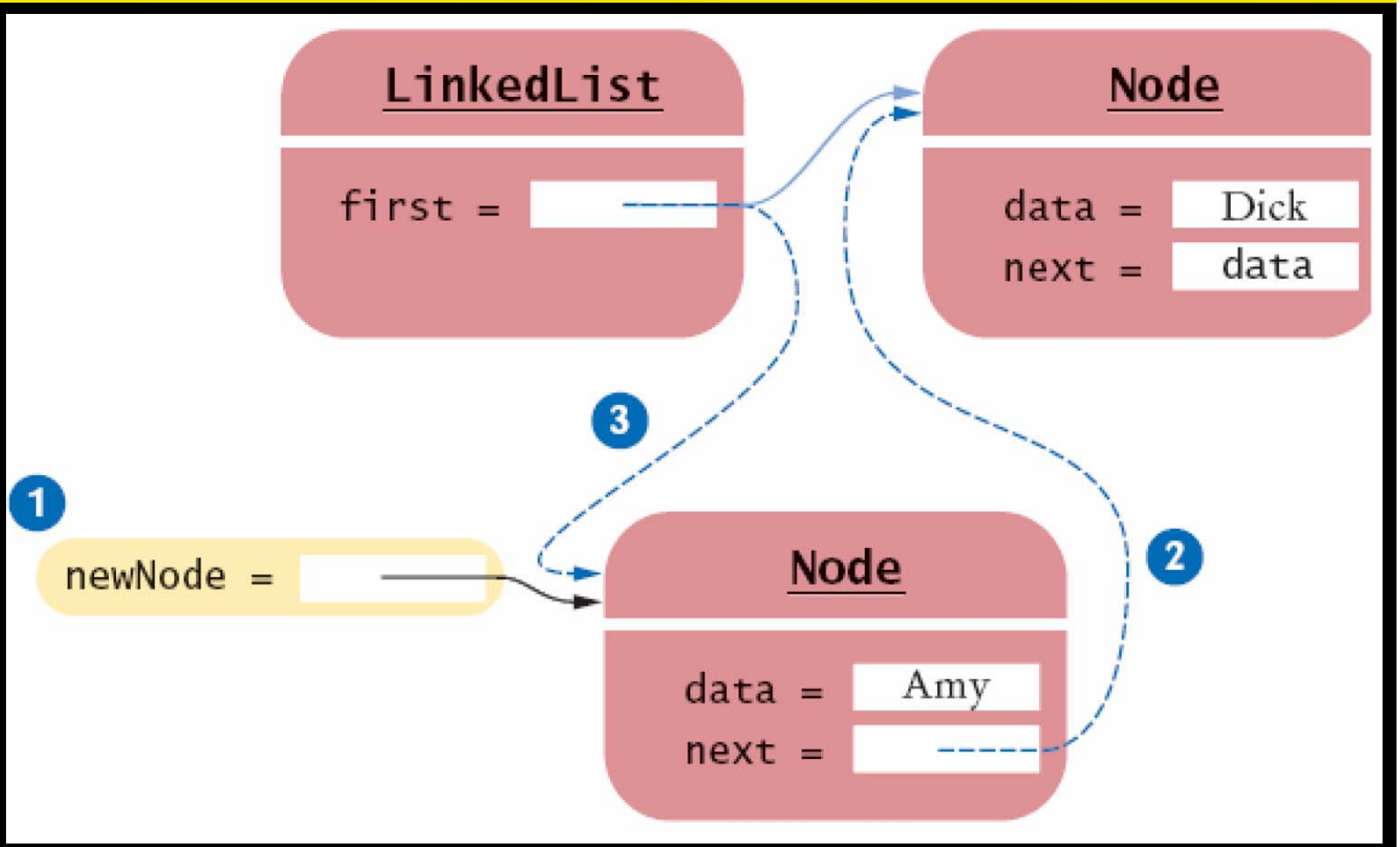


Figure 4: Adding a Node to the Head of a Linked List

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;
   return obj;
   }
   . . .
}
```

Removing the First Node from a Linked List

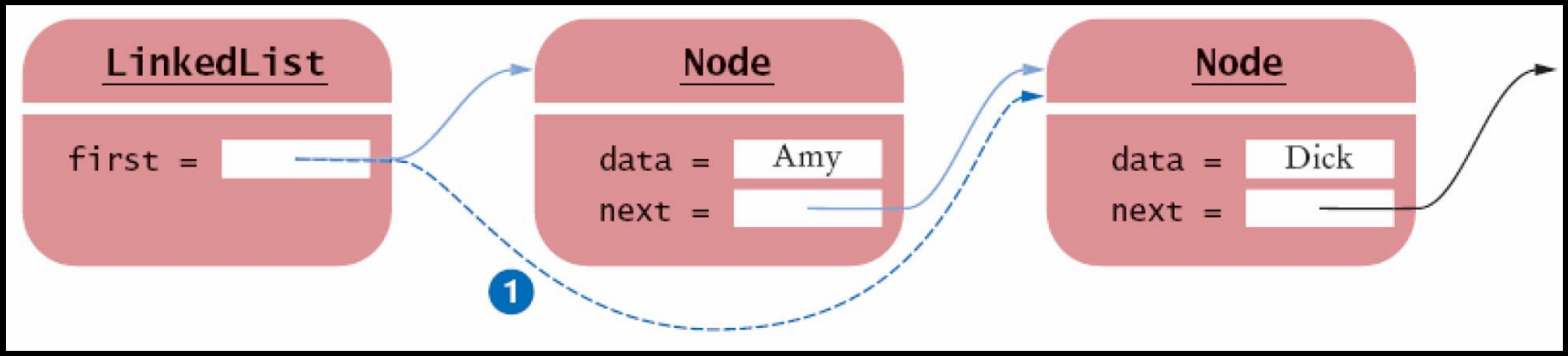


Figure 5:
Removing the First Node from a Linked List

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;
}
```

Removing a Node From the Middle of a Linked List

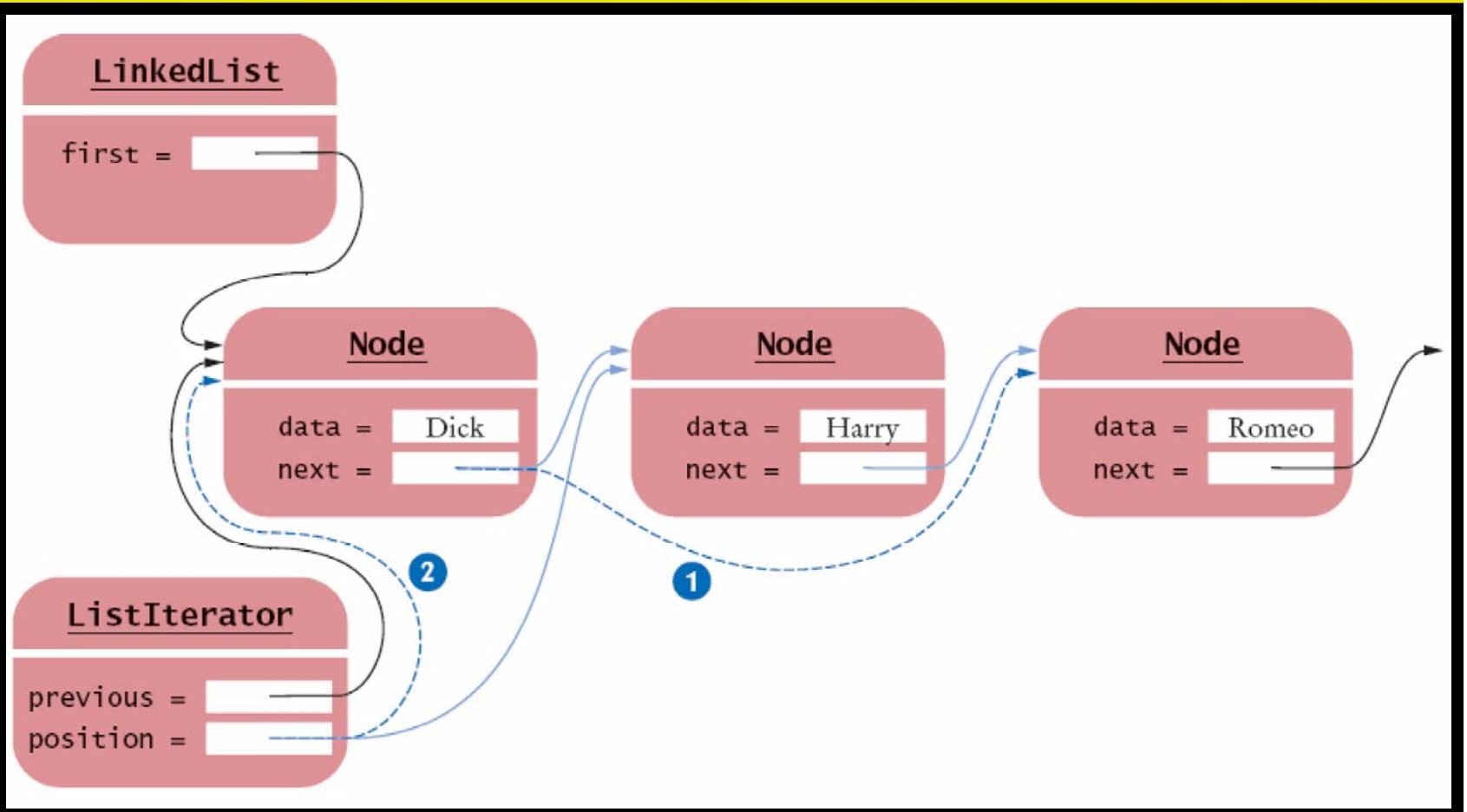


Figure 6:
Removing a Node From the Middle of a Linked List

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;

      newNode.next = position.next;

      position.next = newNode;

      position = newNode;
   }
   previous = position;
}
```

Adding a Node to the Middle of a Linked List

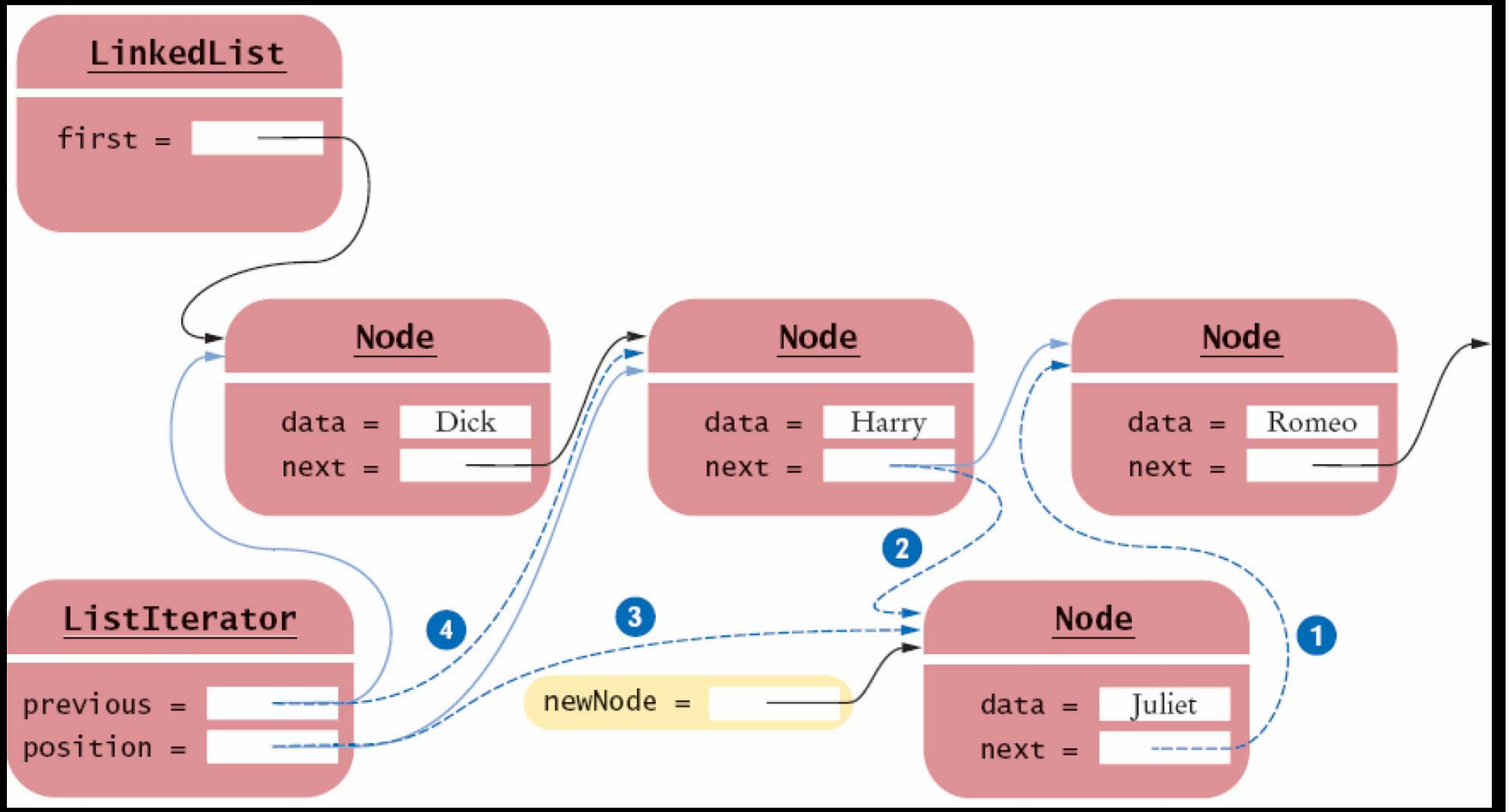


Figure 7:
Adding a Node to the Middle of a Linked List

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: }
```

Self Check

1. Trace through the `addFirst` method when adding an element to an empty list.
2. Conceptually, an iterator points between elements (see Figure 3). Does the position reference point to the element to the left or to the element to the right?
3. Why does the `add` method have two separate cases?

Answers

1. When the list is empty, `first` is `null`. A new Node is allocated. Its `data` field is set to the newly inserted object. Its `next` field is set to `null` because `first` is `null`. The `first` field is set to the new node. The result is a linked list of length 1.
2. It points to the element to the left. You can see that by tracing out the first call to `next`. It leaves position to point to the first node.

Continued

Answers

1. If `position` is `null`, we must be at the head of the list, and inserting an element requires updating the `first` reference. If we are in the middle of the list, the `first` reference should not be changed.

Abstract and Concrete Data Types

- **There are two ways of looking at a linked list**
  - To think of the concrete implementation of such a list
    - Sequence of node objects with links between them
  - Think of the abstract concept of the linked list
    - Ordered sequence of data items that can be traversed with an iterator

Abstract and Concrete Data Types

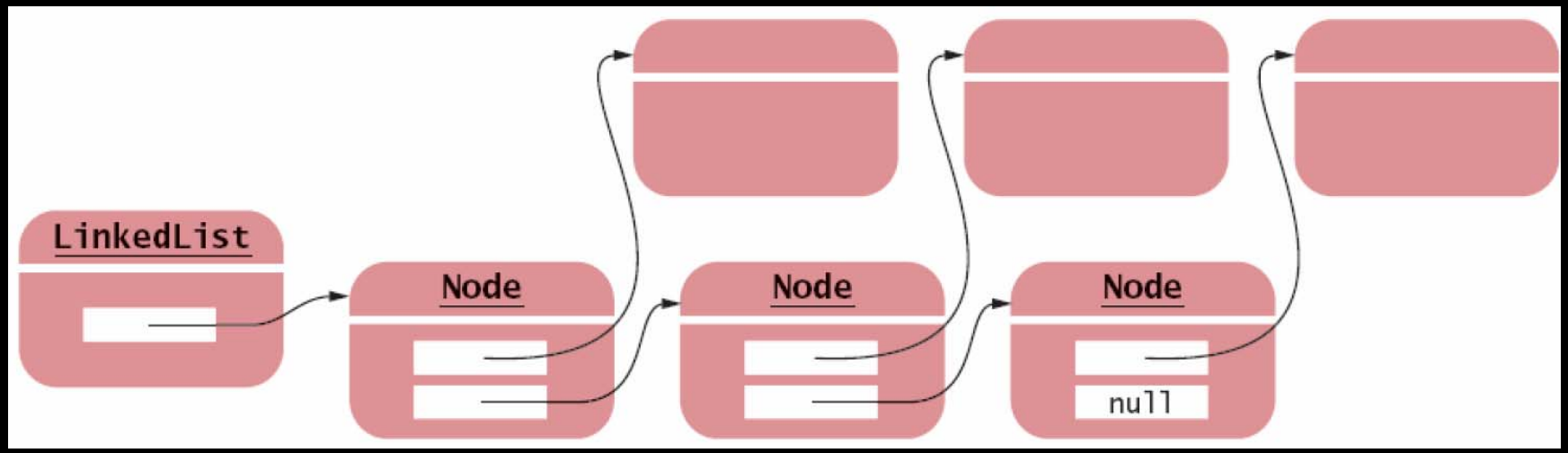


Figure 8:
A Concrete View of a Linked List

Abstract and Concrete Data Types

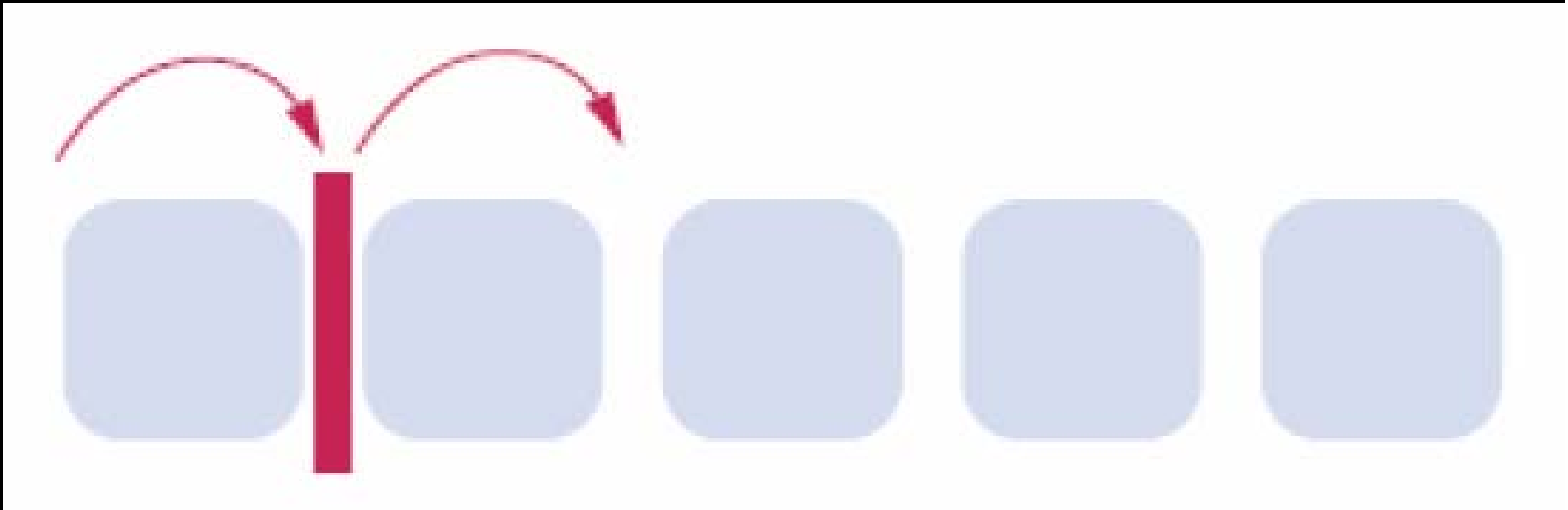


Figure 9:
An Abstract View of a Linked List

Abstract Data Types

- Define the fundamental operations on the data
- Do not specify an implementation

Abstract and Concrete Array Type

- **As with a linked list, there are two ways of looking at an array list**
- **Concrete implementation: a partially filled array of object references**
- **We don't usually think about the concrete implementation when using an array list**
  - We take the abstract point of view
- **Abstract view: ordered sequence of data items, each of which can be accessed by an integer index**

Abstract and Concrete Data Types

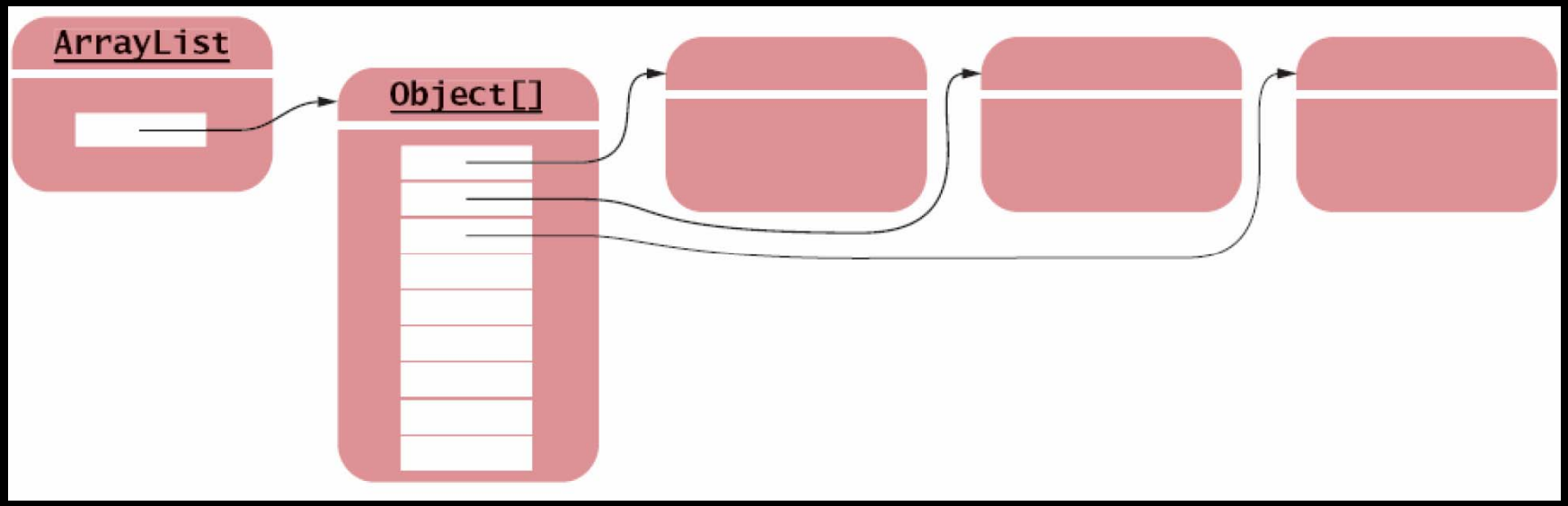


Figure 10:
A Concrete View of an Array List

Abstract and Concrete Data Types

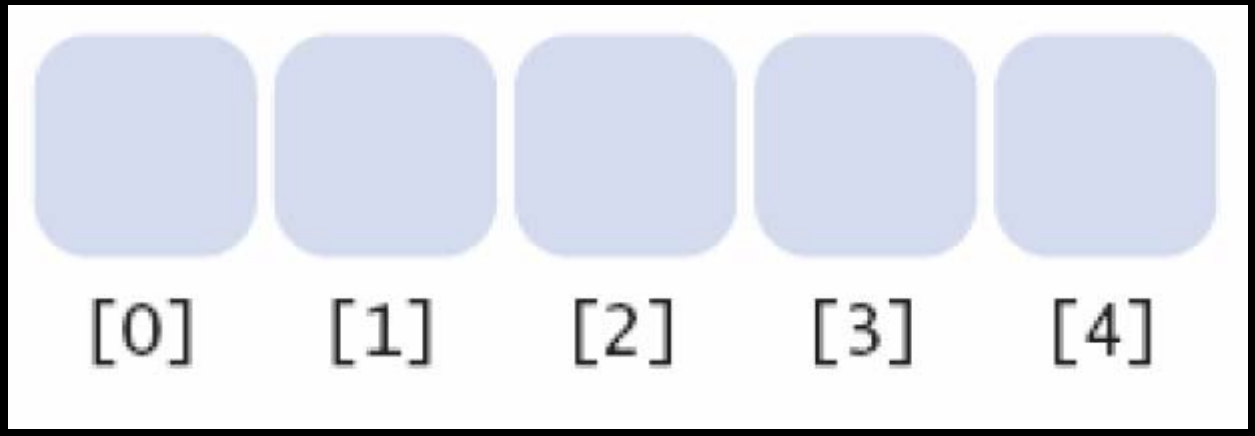


Figure 11:
An Abstract View of an Array List

Abstract and Concrete Data Types

- Concrete implementations of a linked list and an array list are quite different
- The abstractions seem to be similar at first glance
- To see the difference, consider the public interfaces stripped down to their minimal essentials

Fundamental Operations on Array List

```
public class ArrayList
{
   public Object get(int index) { . . . }
   public void set(int index, Object value) { . . . }
   . . .
}
```

Fundamental Operations on Linked List

```
public class LinkedList
{
   public ListIterator listIterator() { . . . }
   . . .
}

public interface ListIterator
{
   Object next();
   boolean hasNext();
   void add(Object value);
   void remove();
   void set(Object value);
   . . .
}
```

Abstract and Concrete Data Types

- **`ArrayList`: combines the interfaces of an array and a list**
- **Both `ArrayList` and `LinkedList` implement an interface called `List`**
  - `List` defines operations for random access and for sequential access
- **Terminology is not in common use outside the Java library**

Continued

Abstract and Concrete Data Types

- More traditional terminology: *array* and *list*
- Java library provides concrete implementations `ArrayList` and `LinkedList` for these abstract types
- Java arrays are another implementation of the abstract array type

Efficiency of Operations for Arrays and Lists

- **Adding or removing an element**
  - 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**
  - 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	$O(n)$	$O(1)$

Abstract Data Types

- **Abstract list**
  - Ordered sequence of items that can be traversed sequentially
  - Allows for insertion and removal of elements at any position
- **Abstract array**
  - Ordered sequence of items with random access via an integer index

Self Check

1. What is the advantage of viewing a type abstractly?
2. How would you sketch an abstract view of a doubly linked list? A concrete view?
3. How much slower is the binary search algorithm for a linked list compared to the linear search algorithm?

Answers

1. You can focus on the essential characteristics of the data type without being distracted by implementation details.
2. The abstract view would be like Figure 9, but with arrows in both directions. The concrete view would be like Figure 8, but with references to the previous node added to each node.

Continued

Answers

1. To locate the middle element takes *n* / 2 steps. To locate the middle of the subinterval to the left or right takes another *n* / 4 steps. The next lookup takes *n* / 8 steps. Thus, we expect almost *n* steps to locate an element. At this point, you are better off just making a linear search that, on average, takes *n* / 2 steps.

Stacks and Queues

- **Stack: collection of items with "last in first out" retrieval**
- **Queue: collection of items with "first in first out" retrieval**

Stack

- **Allows insertion and removal of elements only at one end**
  - Traditionally called the *top* of the stack
- **New items are added to the top of the stack**
- **Items are removed at the top of the stack**
- **Called *last in, first out* or LIFO order**
- **Traditionally, addition and removal operations are called push and pop**
- **Think of a stack of books**

A Stack of Books

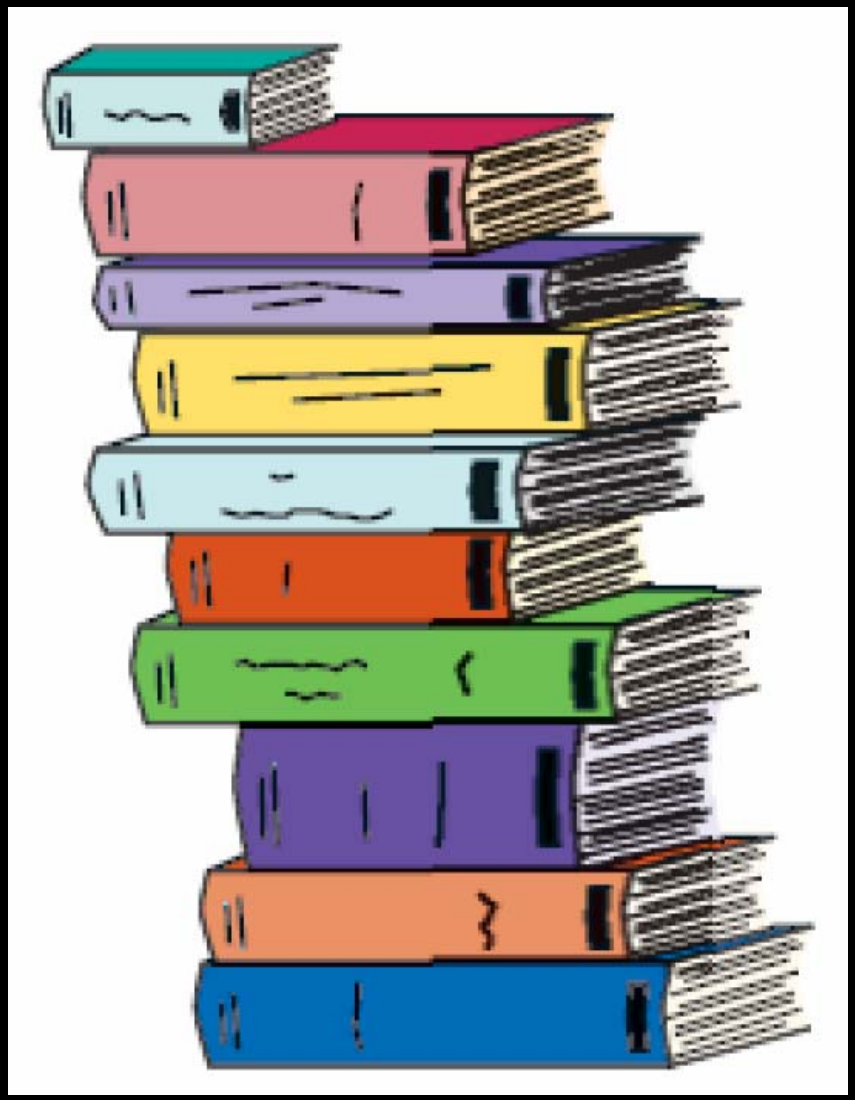


Figure 12:
A Stack of Books

Queue

- **Add items to one end of the queue (the tail)**
- **Remove items from the other end of the queue (the head)**
- **Queues store items in a *first in, first out* or FIFO fashion**
- **Items are removed in the same order in which they have been added**
- **Think of people lining up**
  - People join the tail of the queue and wait until they have reached the head of the queue

A Queue

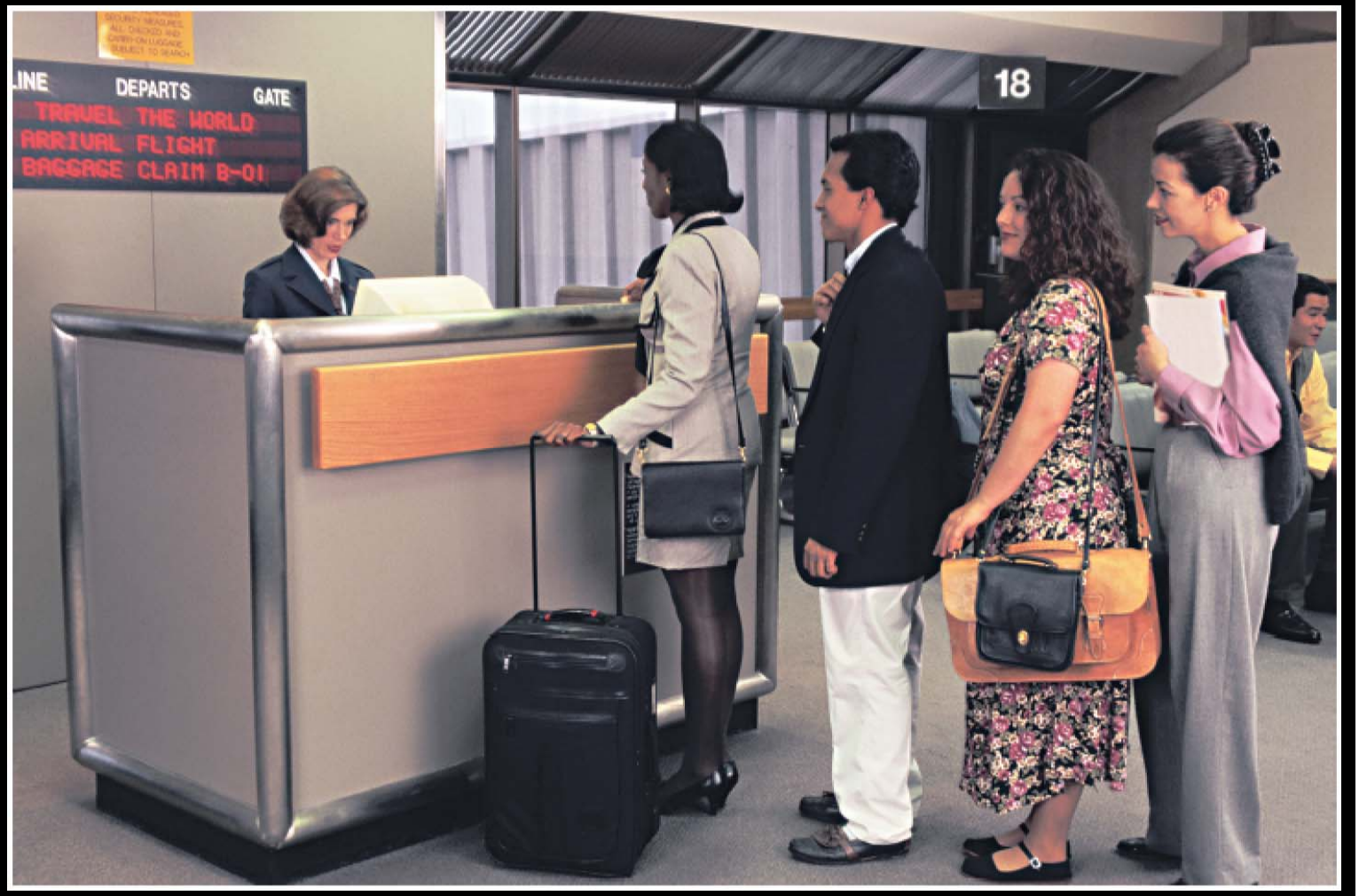


Figure 13: A Queue

Stacks and Queues: Uses in Computer Science

- **Queue**
  - Event queue of all events, kept by the Java GUI system
  - Queue of print jobs
- **Stack**
  - Run-time stack that a processor or virtual machine keeps to organize the variables of nested methods

Abstract Data Type Stack

- `Stack`: concrete implementation of a stack in the Java library

```
Stack<String> s = new Stack<String>();
s.push("A");
s.push("B");
s.push("C");
// The following loop prints C, B, and A
while (s.size() > 0)
   System.out.println(s.pop());
```

- Uses an array to implement a stack

Abstract Data Type Queue

- Queue implementations in the standard library are designed for use with multithreaded programs
- However, it is simple to implement a basic queue yourself

A Queue Implementation

```
public class LinkedListQueue
{
   /**      Constructs an empty queue that uses a linked list.
   */
   public LinkedListQueue()
   {
      list = new LinkedList();
   }
   /**
      Adds an item to the tail of the queue.
      @param x the item to add
   */
   public void add(Object x)
   {
      list.addLast(x);
```

Continued

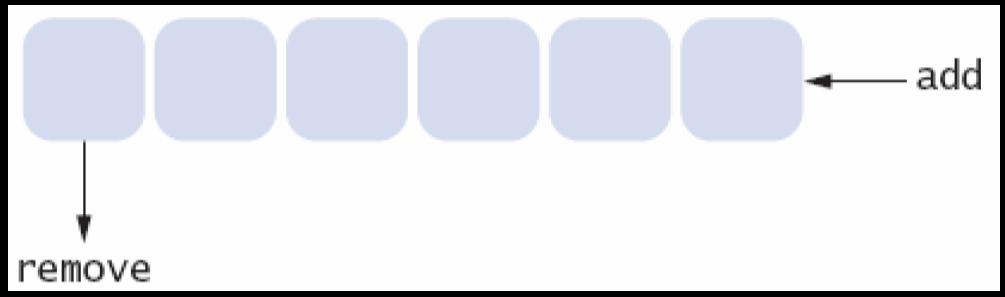
A Queue Implementation

```
   }

   /**
      Removes an item from the head of the queue.
      @return the removed item
   */
   public Object remove()
   {
      return list.removeFirst();
   }

   /**
      Gets the number of items in the queue.
      @return the size
   */
   int size()
   {
      return list.size();
   }
   private LinkedList list;
}
```

Self Check

1. Draw a sketch of the abstract queue type, similar to Figures 9 and 11.
2. Why wouldn't you want to use a stack to manage print jobs?

Answers

1. 

2. **Stacks use a "last in, first out" discipline. If you are the first one to submit a print job and lots of people add print jobs before the printer has a chance to deal with your job, they get their printouts first, and you have to wait until all other jobs are completed.**