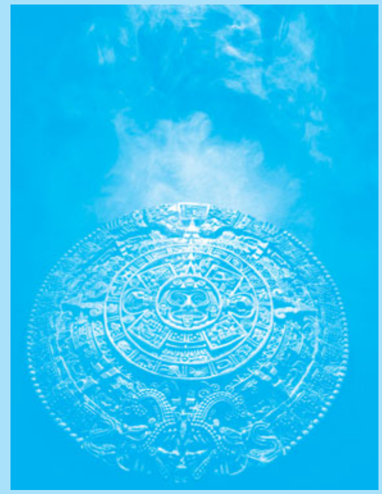
CHAPTER

24

Implementing Lists, Stacks, Queues, and Priority Queues



Objectives

- To design common features of lists in an interface and provide skeleton implementation in a convenience abstract class (§24.2).
- To design and implement an array list using an array (§24.3).
- To design and implement a linked list using a linked structure (§24.4).
- To design and implement a stack class using an array list and a queue class using a linked list (§24.5).
- To design and implement a priority queue using a heap (§24.6).

24.1 Introduction

Key Point

This chapter focuses on implementing data structures.

Lists, stacks, queues, and priority queues are classic data structures typically covered in a data structures course. They are supported in the Java API, and their uses were presented in Chapter 20, Lists, Stacks, Queues, and Priority Queues. This chapter will examine how these data structures are implemented under the hood. Implementation of sets and maps is covered in Chapter 27. Through these examples, you will learn how to design and implement custom data structures.

24.2 Common Features for Lists

Key Point

Common features of lists are defined in the `List` *interface.*

A list is a popular data structure for storing data in sequential order—for example, a list of students, a list of available rooms, a list of cities, a list of books. You can perform the following operations on a list:

- Retrieve an element from the list.
- Insert a new element into the list.
- Delete an element from the list.
- Find out how many elements are in the list.
- Determine whether an element is in the list.
- Check whether the list is empty.

There are two ways to implement a list. One is to use an *array* to store the elements. Array size is fixed. If the capacity of the array is exceeded, you need to create a new, larger array and copy all the elements from the current array to the new array. The other approach is to use a *linked structure*. A linked structure consists of nodes. Each node is dynamically created to hold an element. All the nodes are linked together to form a list. Thus you can define two classes for lists. For convenience, let's name these two classes `MyArrayList` and `MyLinkedList`. These two classes have common operations but different implementations.

convenience abstract class for interface

Design Guide

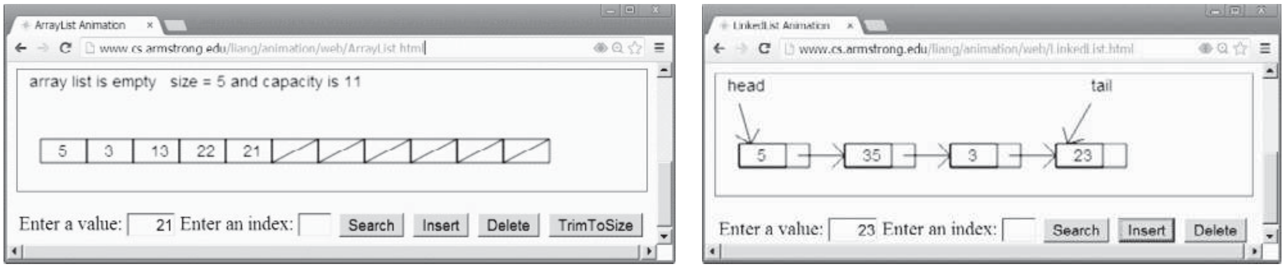
The common operations can be generalized in an interface or an abstract class. A good strategy is to combine the virtues of interfaces and abstract classes by providing both an interface and a convenience abstract class in the design so that the user can use either of them, whichever is convenient. The abstract class provides a skeletal implementation of the interface, which minimizes the effort required to implement the interface.

list animation on Companion Website

Pedagogical Note

For an interactive demo on how array lists and linked lists work, go to www.cs.armstrong.edu/liang/animation/web/ArrayList.html and www.cs.armstrong.edu/liang/animation/web/LinkedList.html, as shown in Figure 24.1.

Let us name the interface `MyList` and the convenience abstract class `MyAbstractList`. Figure 24.2 shows the relationship of `MyList`, `MyAbstractList`, `MyArrayList`, and `MyLinkedList`. The methods in `MyList` and the methods implemented in `MyAbstractList` are shown in Figure 24.3. Listing 24.1 gives the source code for `MyList`.



(a) Array list animation (b) Linked list animation

Figure 24.1 The animation tool enables you to see how array lists and linked lists work.

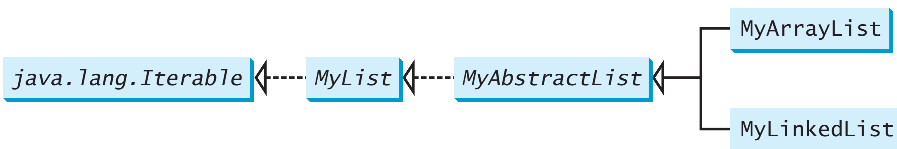


Figure 24.2 `MyList` defines a common interface for `MyAbstractList`, `MyArrayList`, and `MyLinkedList`.

Listing 24.1 MyList.java

```java
public interface MyList<E> extends java.lang.Iterable<E> {
  /** Add a new element at the end of this list */
  public void add(E e);

  /** Add a new element at the specified index in this list */
  public void add(int index, E e);

  /** Clear the list */
  public void clear();

  /** Return true if this list contains the element */
  public boolean contains(E e);

  /** Return the element from this list at the specified index */
  public E get(int index);

  /** Return the index of the first matching element in this list.
   *  Return -1 if no match. */
  public int indexOf(E e);

  /** Return true if this list doesn't contain any elements */
  public boolean isEmpty();

  /** Return the index of the last matching element in this list
   *  Return -1 if no match. */
  public int lastIndexOf(E e);

  /** Remove the first occurrence of the element e from this list.
   *  Shift any subsequent elements to the left.
   *  Return true if the element is removed. */
```

add(e)

add(index, e)

clear()

contains(e)

get(index)

indexOf(e)

isEmpty(e)

lastIndexOf(e)

remove(e)
remove(index)
set(index, e)
size(e)

```
    public boolean remove(E e);

    /** Remove the element at the specified position in this list.
     *  Shift any subsequent elements to the left.
     *  Return the element that was removed from the list. */
    public E remove(int index);

    /** Replace the element at the specified position in this list
     *  with the specified element and return the old element. */
    public Object set(int index, E e);

    /** Return the number of elements in this list */
    public int size();
  }
```

`MyAbstractList` declares variable `size` to indicate the number of elements in the list. The methods `isEmpty()`, `size()`, `add(E)`, and `remove(E)` can be implemented in the class, as shown in Listing 24.2.

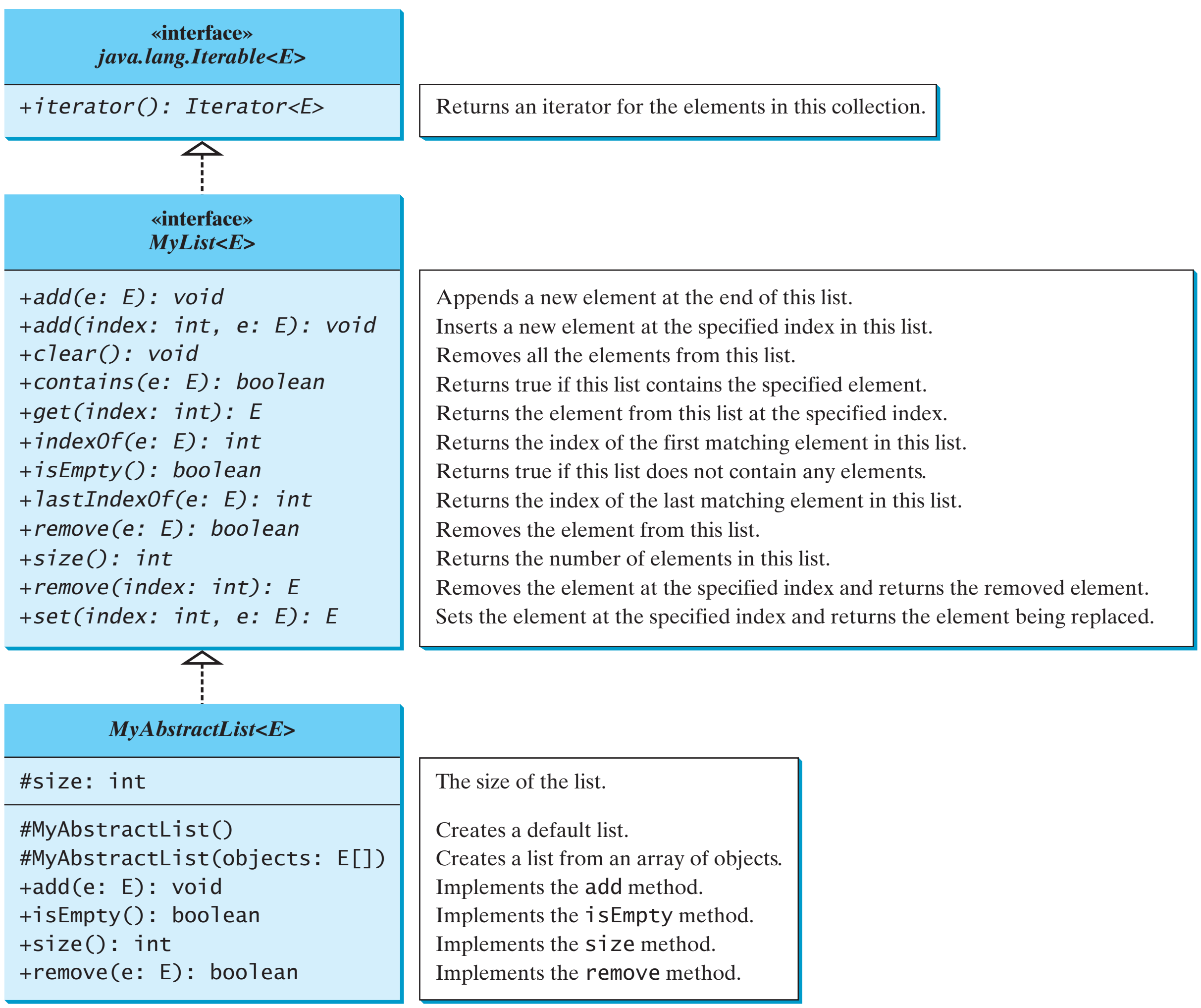


FIGURE 24.3 `MyList` defines the methods for manipulating a list. `MyAbstractList` provides a partial implementation of the `MyList` interface.

LISTING 24.2 MyAbstractList.java

```java
public abstract class MyAbstractList<E> implements MyList<E> {
  protected int size = 0; // The size of the list

  /** Create a default list */
  protected MyAbstractList() {
  }

  /** Create a list from an array of objects */
  protected MyAbstractList(E[] objects) {
    for (int i = 0; i < objects.length; i++)
      add(objects[i]);
  }

  @Override /** Add a new element at the end of this list */
  public void add(E e) {
    add(size, e);
  }

  @Override /** Return true if this list doesn't contain any elements */
  public boolean isEmpty() {
    return size == 0;
  }

  @Override /** Return the number of elements in this list */
  public int size() {
    return size;
  }

  @Override /** Remove the first occurrence of the element e
   *  from this list. Shift any subsequent elements to the left.
   *  Return true if the element is removed. */
  public boolean remove(E e) {
    if (indexOf(e) >= 0) {
      remove(indexOf(e));
      return true;
    }
    else
      return false;
  }
}
```

size

no-arg constructor

constructor

implement `add(E e)`

implement `isEmpty()`

implement `size()`

implement `remove(E e)`

The following sections give the implementation for `MyArrayList` and `MyLinkedList`, respectively.

Design Guide

Protected data fields are rarely used. However, making `size` a protected data field in the `MyAbstractList` class is a good choice. The subclass of `MyAbstractList` can access `size`, but nonsubclasses of `MyAbstractList` in different packages cannot access it. As a general rule, you can declare protected data fields in abstract classes.

protected data field

Check Point

24.1 Suppose `list` is an instance of `MyList`, can you get an iterator for `list` using `list.iterator()`?

24.2 Can you create a list using `new MyAbstractList()` ?

24.3 What methods in `MyList` are overridden in `MyAbstractList`?

24.4 What are the benefits of defining both the `MyList` interface and the `MyAbstractList` class?

24.3 Array Lists

Key Point

An array list is implemented using an array.

An array is a fixed-size data structure. Once an array is created, its size cannot be changed. Nevertheless, you can still use arrays to implement dynamic data structures. The trick is to create a larger new array to replace the current array, if the current array cannot hold new elements in the list.

Initially, an array, say `data` of `E[]` type, is created with a default size. When inserting a new element into the array, first make sure that there is enough room in the array. If not, create a new array twice as large as the current one. Copy the elements from the current array to the new array. The new array now becomes the current array. Before inserting a new element at a specified index, shift all the elements after the index to the right and increase the list size by `1`, as shown in Figure 24.4.

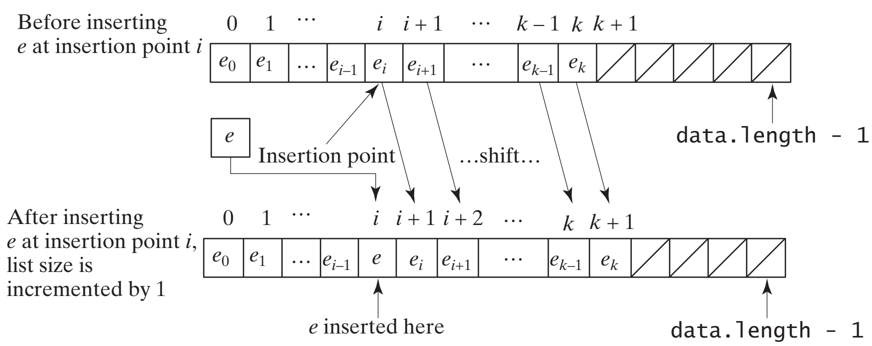


FIGURE 24.4 Inserting a new element into the array requires that all the elements after the insertion point be shifted one position to the right, so that the new element can be inserted at the insertion point.

Note

The data array is of type `E[]`. Each cell in the array actually stores the reference of an object.

To remove an element at a specified index, shift all the elements after the index to the left by one position and decrease the list size by `1`, as shown in Figure 24.5.

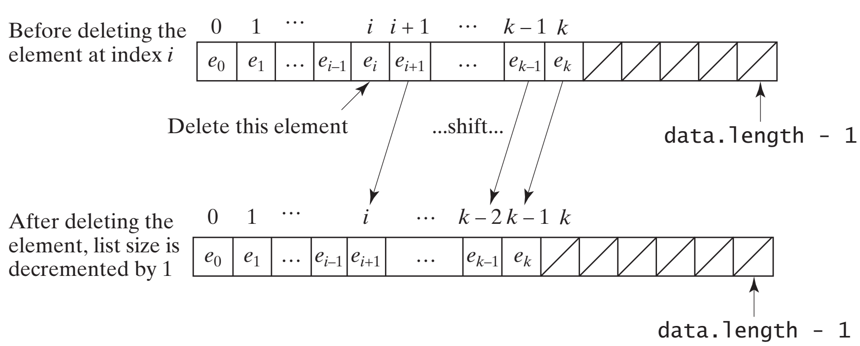


FIGURE 24.5 Deleting an element from the array requires that all the elements after the deletion point be shifted one position to the left.

`MyArrayList` uses an array to implement `MyAbstractList`, as shown in Figure 24.6. Its implementation is given in Listing 24.3.

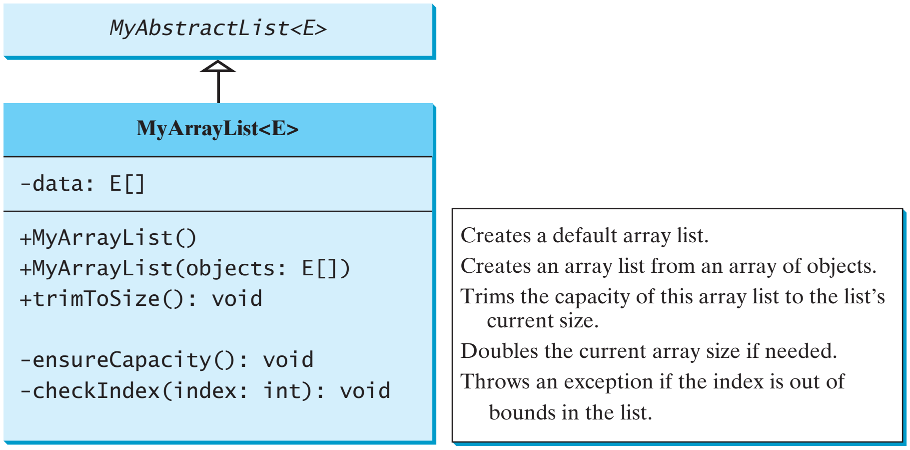


FIGURE 24.6 `MyArrayList` implements a list using an array.

LISTING 24.3 MyArrayList.java

```
public class MyArrayList<E> extends MyAbstractList<E> {
  public static final int INITIAL_CAPACITY = 16;
  private E[] data = (E[]) new Object[INITIAL_CAPACITY];

  /** Create a default list */
  public MyArrayList() {
  }

  /** Create a list from an array of objects */
  public MyArrayList(E[] objects) {
    for (int i = 0; i < objects.length; i++)
      add(objects[i]); // Warning: don't use super(objects)!
  }

  @Override /** Add a new element at the specified index */
  public void add(int index, E e) {
    ensureCapacity();

    // Move the elements to the right after the specified index
    for (int i = size - 1; i >= index; i--)
      data[i + 1] = data[i];

    // Insert new element to data[index]
    data[index] = e;

    // Increase size by 1
    size++;
  }

  /** Create a new larger array, double the current size + 1 */
  private void ensureCapacity() {
    if (size >= data.length) {
      E[] newData = (E[])(new Object[size * 2 + 1]);
      System.arraycopy(data, 0, newData, 0, size);
      data = newData;
    }
  }

```

initial capacity
create an array
no-arg constructor
constructor
add
ensureCapacity
double capacity + 1

clear

```
@Override /** Clear the list */
public void clear() {
  data = (E[])new Object[INITIAL_CAPACITY];
  size = 0;
}
```

contains

```
@Override /** Return true if this list contains the element */
public boolean contains(E e) {
  for (int i = 0; i < size; i++)
    if (e.equals(data[i])) return true;

  return false;
}
```

get

```
@Override /** Return the element at the specified index */
public E get(int index) {
  checkIndex(index);
  return data[index];
}
```

checkIndex

```
private void checkIndex(int index) {
  if (index < 0 || index >= size)
    throw new IndexOutOfBoundsException
      ("index " + index + " out of bounds");
}
```

indexOf

```
@Override /** Return the index of the first matching element
 *  in this list. Return -1 if no match. */
public int indexOf(E e) {
  for (int i = 0; i < size; i++)
    if (e.equals(data[i])) return i;

  return -1;
}
```

lastIndexOf

```
@Override /** Return the index of the last matching element
 *  in this list. Return -1 if no match. */
public int lastIndexOf(E e) {
  for (int i = size - 1; i >= 0; i--)
    if (e.equals(data[i])) return i;

  return -1;
}
```

remove

```
@Override /** Remove the element at the specified position
 *  in this list. Shift any subsequent elements to the left.
 *  Return the element that was removed from the list. */
public E remove(int index) {
  checkIndex(index);

  E e = data[index];

  // Shift data to the left
  for (int j = index; j < size - 1; j++)
    data[j] = data[j + 1];

  data[size - 1] = null; // This element is now null

  // Decrement size
  size--;
```

```
    return e;
  }

  @Override /** Replace the element at the specified position
    *  in this list with the specified element. */
  public E set(int index, E e) {
    checkIndex(index);
    E old = data[index];
    data[index] = e;
    return old;
  }

  @Override
  public String toString() {
    StringBuilder result = new StringBuilder("[");

    for (int i = 0; i < size; i++) {
      result.append(data[i]);
      if (i < size - 1) result.append(", ");
    }

    return result.toString() + "]";
  }

  /** Trims the capacity to current size */
  public void trimToSize() {
    if (size != data.length) {
      E[] newData = (E[])(new Object[size]);
      System.arraycopy(data, 0, newData, 0, size);
      data = newData;
    } // If size == capacity, no need to trim
  }

  @Override /** Override iterator() defined in Iterable */
  public java.util.Iterator<E> iterator() {
    return new ArrayListIterator();
  }

  private class ArrayListIterator
      implements java.util.Iterator<E> {
    private int current = 0; // Current index

    @Override
    public boolean hasNext() {
      return (current < size);
    }

    @Override
    public E next() {
      return data[current++];
    }

    @Override
    public void remove() {
      MyArrayList.this.remove(current);
    }
  }
}
```

set

toString

trimToSize

iterator

The constant `INITIAL_CAPACITY` (line 2) is used to create an initial array `data` (line 3). Owing to generics type erasure, you cannot create a generic array using the syntax `new e[INITIAL_CAPACITY]`. To circumvent this limitation, an array of the `Object` type is created in line 3 and cast into `E[]`.

Note that the implementation of the second constructor in `MyArrayList` is the same as for `MyAbstractList`. Can you replace lines 11–12 with `super(objects)`? See Checkpoint Question 24.8 for answers.

add

The `add(int index, E e)` method (lines 16–28) inserts element `e` at the specified `index` in the array. This method first invokes `ensureCapacity()` (line 17), which ensures that there is a space in the array for the new element. It then shifts all the elements after the index one position to the right before inserting the element (lines 20–21). After the element is added, `size` is incremented by `1` (line 27). Note that the variable `size` is defined as `protected` in `MyAbstractList`, so it can be accessed in `MyArrayList`.

ensureCapacity

The `ensureCapacity()` method (lines 31–37) checks whether the array is full. If so, the program creates a new array that doubles the current array size + 1, copies the current array to the new array using the `System.arraycopy` method, and sets the new array as the current array.

clear

The `clear()` method (lines 40–43) creates a new array using the size as `INITIAL_CAPACITY` and resets the variable `size` to `0`. The class will work if line 41 is deleted. However, the class will have a memory leak, because the elements are still in the array, although they are no longer needed. By creating a new array and assigning it to `data`, the old array and the elements stored in the old array become garbage, which will be automatically collected by the JVM.

contains

The `contains(E e)` method (lines 46–51) checks whether element `e` is contained in the array by comparing `e` with each element in the array using the `equals` method.

The `get(int index)` method (lines 54–57) checks if `index` is within the range and returns `data[index]` if `index` is in the range.

checkIndex

The `checkIndex(int index)` method (lines 59–63) checks if `index` is within the range. If not, the method throws an `IndexOutOfBoundsException` (line 61).

indexOf

The `indexOf(E e)` method (lines 67–72) compares element `e` with the elements in the array, starting from the first one. If a match is found, the index of the element is returned; otherwise, `-1` is returned.

lastIndexOf

The `lastIndexOf(E e)` method (lines 76–81) compares element `e` with the elements in the array, starting from the last one. If a match is found, the index of the element is returned; otherwise, `-1` is returned.

remove

The `remove(int index)` method (lines 86–101) shifts all the elements after the index one position to the left (lines 92–93) and decrements `size` by `1` (line 98). The last element is not used anymore and is set to `null` (line 95).

set

The `set(int index, E e)` method (lines 105–110) simply assigns `e` to `data[index]` to replace the element at the specified index with element `e`.

toString

The `toString()` method (lines 113–122) overrides the `toString` method in the `Object` class to return a string representing all the elements in the list.

trimToSize

The `trimToSize()` method (lines 125–131) creates a new array whose size matches the current array-list size (line 127), copies the current array to the new array using the `System.arraycopy` method (line 128), and sets the new array as the current array (line 129). Note that if `size == capacity`, there is no need to trim the size of the array.

iterator

The `iterator()` method defined in the `java.lang.Iterable` interface is implemented to return an instance on `java.util.Iterator` (lines 134–136). The `ArrayListIterator` class implements `Iterator` with concrete methods for `hasNext`, `next`, and `remove` (lines 143–155). It uses `current` to denote the current position of the element being traversed (line 140).

Listing 24.4 gives an example that creates a list using `MyArrayList`. It uses the `add` method to add strings to the list and the `remove` method to remove strings. Since

`MyArrayList` implements `Iterable`, the elements can be traversed using a for-each loop (lines 35–36).

LISTING 24.4 TestMyArrayList.java

```
 1 public class TestMyArrayList {
 2   public static void main(String[] args) {
 3     // Create a list
 4     MyList<String> list = new MyArrayList<String>();
 5
 6     // Add elements to the list
 7     list.add("America"); // Add it to the list
 8     System.out.println("(1) " + list);
 9
10     list.add(0, "Canada"); // Add it to the beginning of the list
11     System.out.println("(2) " + list);
12
13     list.add("Russia"); // Add it to the end of the list
14     System.out.println("(3) " + list);
15
16     list.add("France"); // Add it to the end of the list
17     System.out.println("(4) " + list);
18
19     list.add(2, "Germany"); // Add it to the list at index 2
20     System.out.println("(5) " + list);
21
22     list.add(5, "Norway"); // Add it to the list at index 5
23     System.out.println("(6) " + list);
24
25     // Remove elements from the list
26     list.remove("Canada"); // Same as list.remove(0) in this case
27     System.out.println("(7) " + list);
28
29     list.remove(2); // Remove the element at index 2
30     System.out.println("(8) " + list);
31
32     list.remove(list.size() - 1); // Remove the last element
33     System.out.print("(9) " + list + "\n(10) ");
34
35     for (String s: list)
36       System.out.print(s.toUpperCase() + " ");
37   }
38 }
```

create a list

add to list

remove from list

using iterator

```
(1) [America]
(2) [Canada, America]
(3) [Canada, America, Russia]
(4) [Canada, America, Russia, France]
(5) [Canada, America, Germany, Russia, France]
(6) [Canada, America, Germany, Russia, France, Norway]
(7) [America, Germany, Russia, France, Norway]
(8) [America, Germany, France, Norway]
(9) [America, Germany, France]
(10) AMERICA GERMANY FRANCE
```

Check Point

24.5 What are the limitations of the array data type?

24.6 `MyArrayList` is implemented using an array, and an array is a fixed-size data structure. Why is `MyArrayList` considered a dynamic data structure?

24.7 Show the length of the array in `MyArrayList` after each of the following statements is executed.

```
MyArrayList<Double> list = new MyArrayList<>();
list.add(1.5);
list.trimToSize();
list.add(3.4);
list.add(7.4);
list.add(17.4);
```

24.8 What is wrong if lines 11–12 in Listing 24.3, MyArrayList.java,

```
  for (int i = 0; i < objects.length; i++)
    add(objects[i]);
```

are replaced by

```
super(objects);
```

or

```
data = objects;
size = objects.length;
```

24.9 If you change the code in line 33 in Listing 24.3, MyArrayList.java, from

```
E[] newData = (E[])(new Object[size * 2 + 1]);
```

to

```
E[] newData = (E[])(new Object[size * 2]);
```

the program is incorrect. Can you find the reason?

24.10 Will the `MyArrayList` class have memory leak if the following code in line 41 is deleted?

```
data = (E[])new Object[INITIAL_CAPACITY];
```

24.11 The `get(index)` method invokes the `checkIndex(index)` method (lines 59–63 in Listing 24.3) to throw an `IndexOutOfBoundsException` if the index is out of bounds. Suppose the `add(index, e)` is implemented as follows:

```
public void add(int index, E e) {
  checkIndex(index);

  // Same as lines 17-27 in Listing 24.3 MyArrayList.java
}
```

What will happen if you run the following code?

```
MyArrayList<String> list = new MyArrayList<>();
list.add("New York");
```

24.4 Linked Lists

Key Point

A linked list is implemented using a linked structure.

Since `MyArrayList` is implemented using an array, the methods `get(int index)` and `set(int index, E e)` for accessing and modifying an element through an index and the `add(E e)` method for adding an element at the end of the list are efficient. However, the methods `add(int index, E e)` and `remove(int index)` are inefficient, because they require shifting a potentially large number of elements. You can use a linked structure to implement a list to improve efficiency for adding and removing an element at the beginning of a list.

24.4.1 Nodes

In a linked list, each element is contained in an object, called the *node*. When a new element is added to the list, a node is created to contain it. Each node is linked to its next neighbor, as shown in Figure 24.7.

A node can be created from a class defined as follows:

```
class Node<E> {
  E element;
  Node<E> next;

  public Node(E e) {
    element = e;
  }
}
```

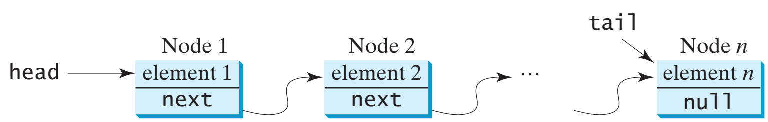


FIGURE 24.7 A linked list consists of any number of nodes chained together.

We use the variable `head` to refer to the first node in the list, and the variable `tail` to the last node. If the list is empty, both `head` and `tail` are `null`. Here is an example that creates a linked list to hold three nodes. Each node stores a string element.

Step 1: Declare `head` and `tail`.

```
Node<String> head = null;
Node<String> tail = null;
```

The list is empty now

`head` and `tail` are both `null`. The list is empty.

Step 2: Create the first node and append it to the list, as shown in Figure 24.8. After the first node is inserted in the list, `head` and `tail` point to this node.

```
head = new Node<>("Chicago");
tail = head;
```

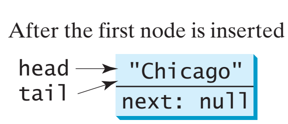


FIGURE 24.8 Append the first node to the list. Both head and tail point to this node.

Step 3: Create the second node and append it into the list, as shown in Figure 24.9a. To append the second node to the list, link the first node with the new node. The new node is now the tail node, so you should move `tail` to point to this new node, as shown in Figure 24.9b.

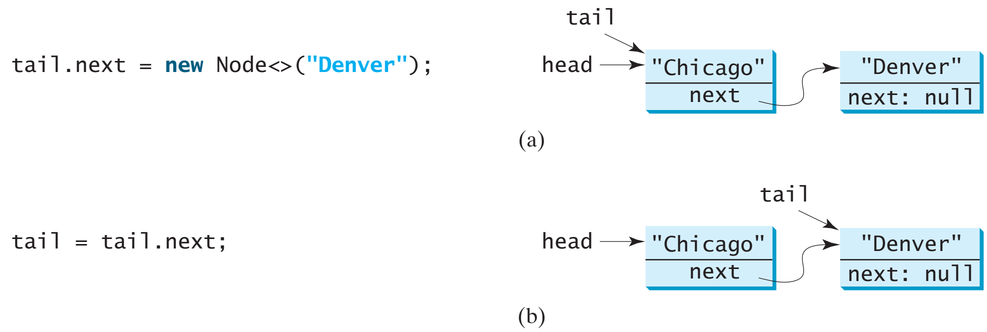


FIGURE 24.9 Append the second node to the list. Tail now points to this new node.

Step 4: Create the third node and append it to the list, as shown in Figure 24.10a. To append the new node to the list, link the last node in the list with the new node. The new node is now the tail node, so you should move **`tail`** to point to this new node, as shown in Figure 24.10b.

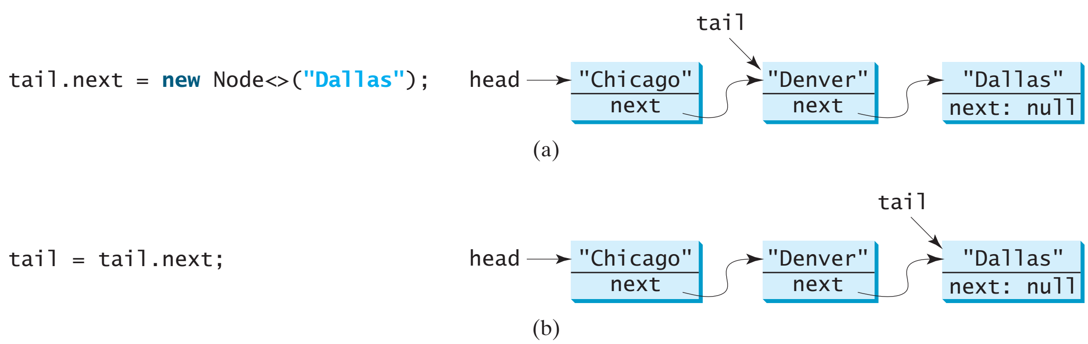


FIGURE 24.10 Append the third node to the list.

Each node contains the element and a data field named **`next`** that points to the next element. If the node is the last in the list, its pointer data field **`next`** contains the value **`null`**. You can use this property to detect the last node. For example, you can write the following loop to traverse all the nodes in the list.

current pointer
check last node
next node

```
1 Node current = head;
2 while (current != null) {
3   System.out.println(current.element);
4   current = current.next;
5 }
```

The variable **`current`** points initially to the first node in the list (line 1). In the loop, the element of the current node is retrieved (line 3), and then **`current`** points to the next node (line 4). The loop continues until the current node is **`null`**.

24.4.2 The `MyLinkedList` Class

The **`MyLinkedList`** class uses a linked structure to implement a dynamic list. It extends **`MyAbstractList`**. In addition, it provides the methods **`addFirst`**, **`addLast`**, **`removeFirst`**, **`removeLast`**, **`getFirst`**, and **`getLast`**, as shown in Figure 24.11.

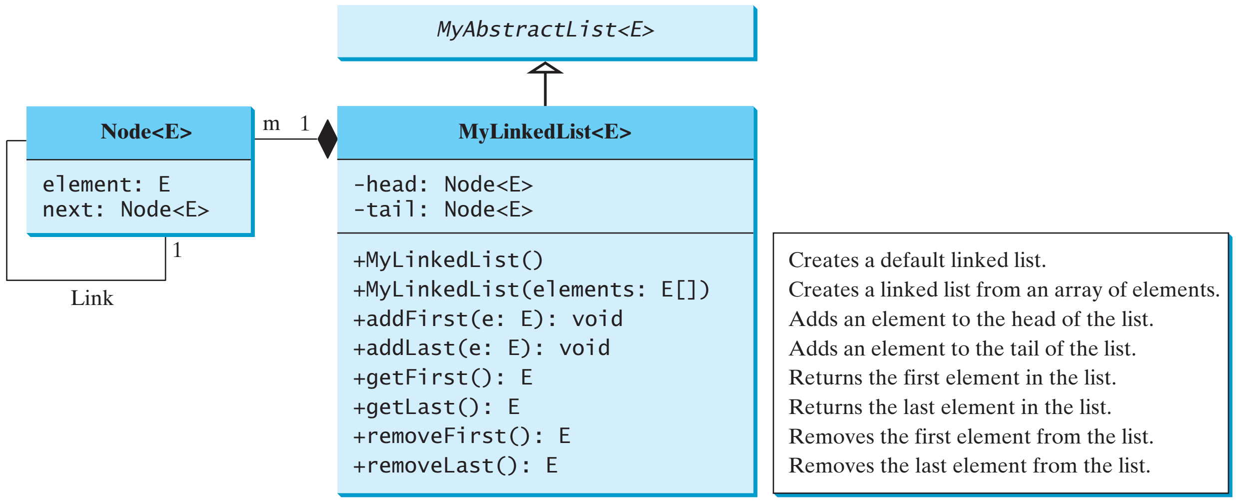


FIGURE 24.11 `MyLinkedList` implements a list using a linked list of nodes.

Assuming that the class has been implemented, Listing 24.5 gives a test program that uses the class.

LISTING 24.5 TestMyLinkedList.java

```java
public class TestMyLinkedList {
  /** Main method */
  public static void main(String[] args) {
    // Create a list for strings
    MyLinkedList<String> list = new MyLinkedList<>();

    // Add elements to the list
    list.add("America"); // Add it to the list
    System.out.println("(1) " + list);

    list.add(0, "Canada"); // Add it to the beginning of the list
    System.out.println("(2) " + list);

    list.add("Russia"); // Add it to the end of the list
    System.out.println("(3) " + list);

    list.addLast("France"); // Add it to the end of  the list
    System.out.println("(4) " + list);

    list.add(2, "Germany"); // Add it to the list at index 2
    System.out.println("(5) " + list);

    list.add(5, "Norway"); // Add it to the list at index 5
    System.out.println("(6) " + list);

    list.add(0, "Poland"); // Same as list.addFirst("Poland")
    System.out.println("(7) " + list);

    // Remove elements from the list
    list.remove(0);// Same as list.remove("Poland") in this case
    System.out.println("(8) " + list);
```

create list
append element
print list
insert element
append element
append element
insert element
insert element
insert element
remove element

remove element
remove element
traverse using iterator

```

    list.remove(2); // Remove the element at index 2
    System.out.println("(9) " + list);

    list.remove(list.size() - 1); // Remove the last element
    System.out.print("(10) " + list + "\n(11) ");

    for (String s: list)
      System.out.print(s.toUpperCase() + " ");
  }
}
```

```
(1) [America]
(2) [Canada, America]
(3) [Canada, America, Russia]
(4) [Canada, America, Russia, France]
(5) [Canada, America, Germany, Russia, France]
(6) [Canada, America, Germany, Russia, France, Norway]
(7) [Poland, Canada, America, Germany, Russia, France, Norway]
(8) [Canada, America, Germany, Russia, France, Norway]
(9) [Canada, America, Russia, France, Norway]
(10) [Canada, America, Russia, France]
(11) CANADA AMERICA RUSSIA FRANCE
```

24.4.3 Implementing **MyLinkedList**

Now let us turn our attention to implementing the **MyLinkedList** class. We will discuss how to implement the methods **addFirst**, **addLast**, **add(index, e)**, **removeFirst**, **removeLast**, and **remove(index)** and leave the other methods in the **MyLinkedList** class as exercises.

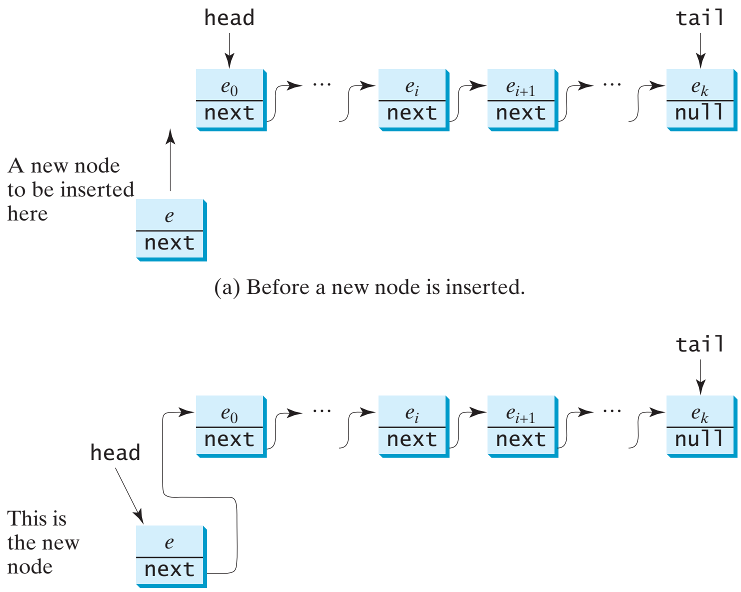
24.4.3.1 Implementing **addFirst(e)**

The **addFirst(e)** method creates a new node for holding element **e**. The new node becomes the first node in the list. It can be implemented as follows:

create a node
link with head
head to new node
increase size
was empty?

```
1 public void addFirst(E e) {
2   Node<E> newNode = new Node<>(e); // Create a new node
3   newNode.next = head; // link the new node with the head
4   head = newNode; // head points to the new node
5   size++; // Increase list size
6
7   if (tail == null) // The new node is the only node in list
8     tail = head;
9 }
```

The **addFirst(e)** method creates a new node to store the element (line 2) and inserts the node at the beginning of the list (line 3), as shown in Figure 24.12a. After the insertion, **head** should point to this new element node (line 4), as shown in Figure 24.12b.



(b) After a new node is inserted.

FIGURE 24.12 A new element is added to the beginning of the list.

If the list is empty (line 7), both **head** and **tail** will point to this new node (line 8). After the node is created, **size** should be increased by **1** (line 5).

24.4.3.2 Implementing **addLast(e)**

The **addLast(e)** method creates a node to hold the element and appends the node at the end of the list. It can be implemented as follows:

```
1  public void addLast(E e) {
2    Node<E> newNode = new Node<>(e); // Create a new node for e
3
4    if (tail == null) {
5      head = tail = newNode; // The only node in list
6    }
7    else {
8      tail.next = newNode; // Link the new node with the last node
9      tail = tail.next; // tail now points to the last node
10   }
11
12   size++; // Increase size
13 }
```

create a node

increase size

The **addLast(e)** method creates a new node to store the element (line 2) and appends it to the end of the list. Consider two cases:

1. If the list is empty (line 4), both **head** and **tail** will point to this new node (line 5);
2. Otherwise, link the node with the last node in the list (line 8). **tail** should now point to this new node (line 9). Figure 24.13a and Figure 24.13b show the new node for element **e** before and after the insertion.

In any case, after the node is created, the **size** should be increased by **1** (line 12).

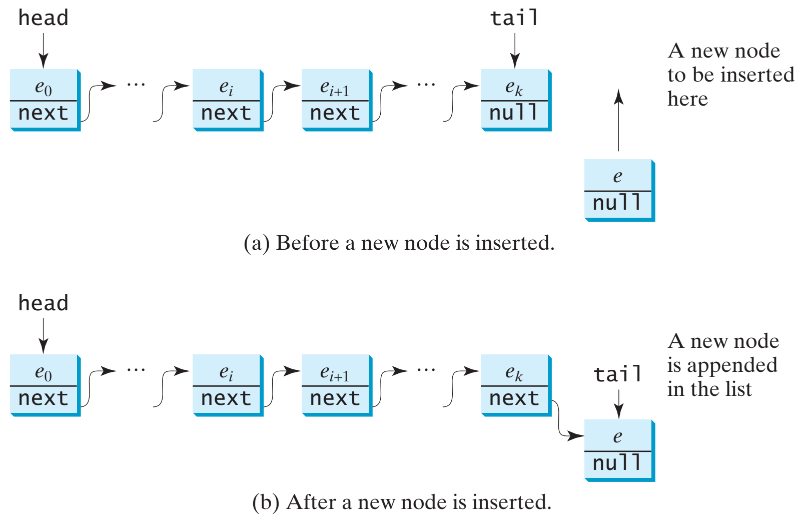


FIGURE 24.13 A new element is added at the end of the list.

24.4.3.3 Implementing `add(index, e)`

The `add(index, e)` method inserts an element into the list at the specified index. It can be implemented as follows:

insert first
insert last
create a node
increase size

```
1  public void add(int index, E e) {
2    if (index == 0) addFirst(e); // Insert first
3    else if (index >= size) addLast(e); // Insert last
4    else { // Insert in the middle
5      Node<E> current = head;
6      for (int i = 1; i < index; i++)
7        current = current.next;
8      Node<E> temp = current.next;
9      current.next = new Node<E>(e);
10     (current.next).next = temp;
11     size++;
12   }
13 }
```

There are three cases when inserting an element into the list:

1. If `index` is `0`, invoke `addFirst(e)` (line 2) to insert the element at the beginning of the list.
2. If `index` is greater than or equal to `size`, invoke `addLast(e)` (line 3) to insert the element at the end of the list.
3. Otherwise, create a new node to store the new element and locate where to insert it. As shown in Figure 24.14a, the new node is to be inserted between the nodes `current` and `temp`. The method assigns the new node to `current.next` and assigns `temp` to the new node's `next`, as shown in Figure 24.14b. The size is now increased by `1` (line 11).

24.4.3.4 Implementing `removeFirst()`

The `removeFirst()` method removes the first element from the list. It can be implemented as follows:

nothing to remove

```
public E removeFirst() {
  if (size == 0) return null; // Nothing to delete
  else {
```

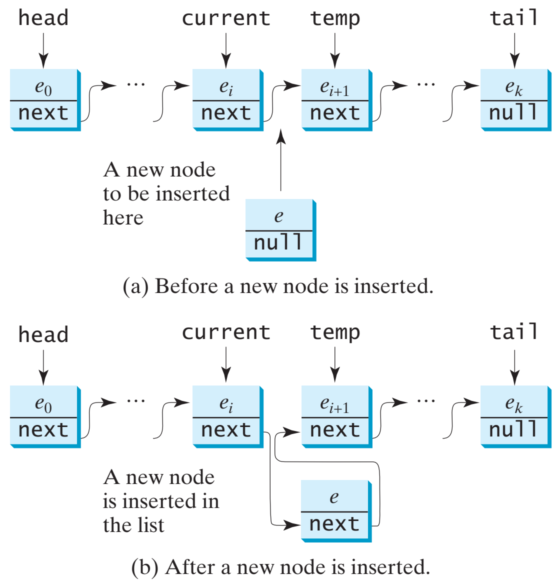


FIGURE 24.14 A new element is inserted in the middle of the list.

```
4       Node<E> temp = head; // Keep the first node temporarily
5       head = head.next; // Move head to point to next node
6       size--; // Reduce size by 1
7       if (head == null) tail = null; // List becomes empty
8       return temp.element; // Return the deleted element
9     }
10  }
```

keep old head
new head
decrease `size`
destroy the node

Consider two cases:

1. If the list is empty, there is nothing to delete, so return **`null`** (line 2).
2. Otherwise, remove the first node from the list by pointing **`head`** to the second node. Figure 24.15a and Figure 24.15b show the linked list before and after the deletion. The size is reduced by **`1`** after the deletion (line 6). If the list becomes empty, after removing the element, **`tail`** should be set to **`null`** (line 7).

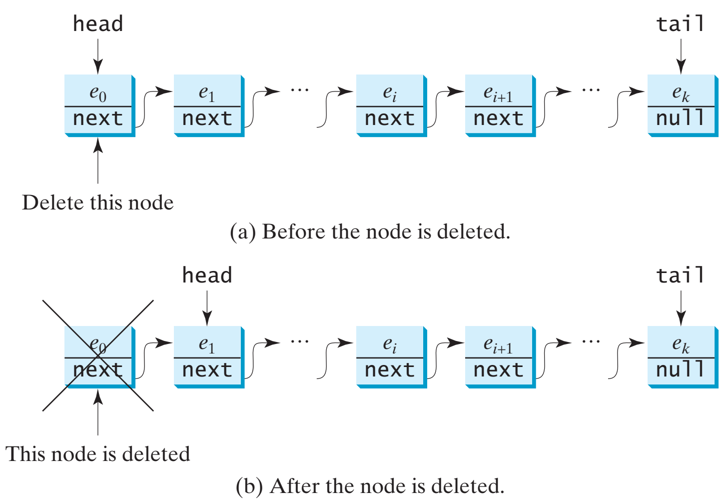


FIGURE 24.15 The first node is deleted from the list.

24.4.3.5 Implementing `removeLast()`

The `removeLast()` method removes the last element from the list. It can be implemented as follows:

empty?
size 1?
head and `tail` `null`
`size` is 0
return element
`size` > 1
move tail
reduce size
return element

```
1  public E removeLast() {
2    if (size == 0) return null; // Nothing to remove
3    else if (size == 1) { // Only one element in the list
4      Node<E> temp = head;
5      head = tail = null; // list becomes empty
6      size = 0;
7      return temp.element;
8    }
9    else {
10     Node<E> current = head;
11
12     for (int i = 0; i < size - 2; i++)
13       current = current.next;
14
15     Node<E> temp = tail;
16     tail = current;
17     tail.next = null;
18     size--;
19     return temp.element;
20   }
21 }
```

Consider three cases:

1. If the list is empty, return `null` (line 2).
2. If the list contains only one node, this node is destroyed; `head` and `tail` both become `null` (line 5). The size becomes `0` after the deletion (line 6) and the element value of the deleted node is returned (line 7).
3. Otherwise, the last node is destroyed (line 17) and the `tail` is repositioned to point to the second-to-last node. Figure 24.16a and Figure 24.16b show the last node before and after it is deleted. The size is reduced by `1` after the deletion (line 18) and the element value of the deleted node is returned (line 19).

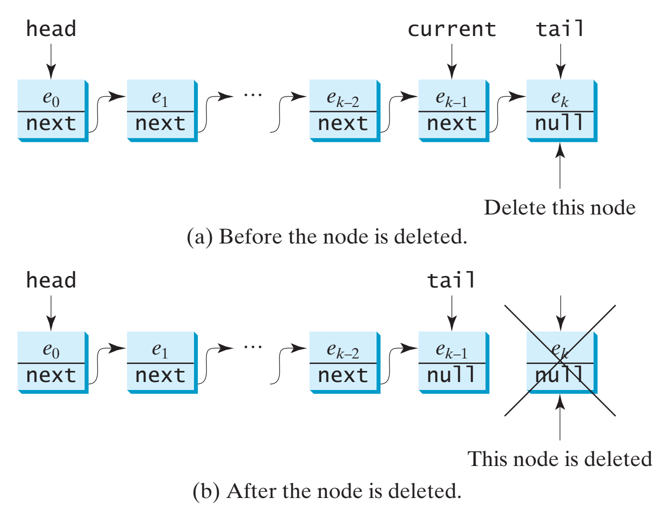


FIGURE 24.16 The last node is deleted from the list.

24.4.3.6 Implementing `remove(index)`

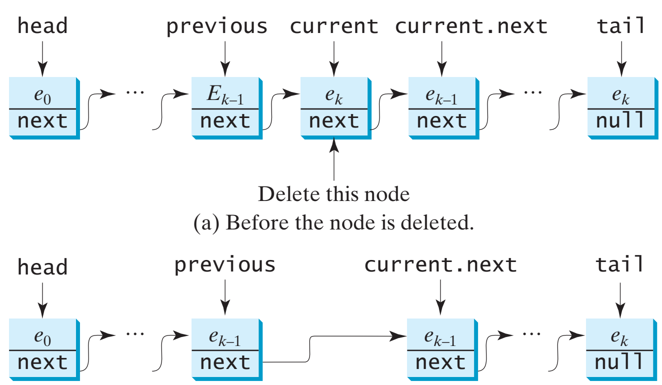
The `remove(index)` method finds the node at the specified index and then removes it. It can be implemented as follows:

```
1  public E remove(int index) {
2    if (index < 0 || index >= size) return null; // Out of range
3    else if (index == 0) return removeFirst(); // Remove first
4    else if (index == size - 1) return removeLast(); // Remove last
5    else {
6      Node<E> previous = head;
7
8      for (int i = 1; i < index; i++) {
9        previous = previous.next;
10     }
11
12     Node<E> current = previous.next;
13     previous.next = current.next;
14     size--;
15     return current.element;
16   }
17 }
```

out of range
remove first
remove last
locate previous
locate current
remove from list
reduce size
return element

Consider four cases:

1. If `index` is beyond the range of the list (i.e., `index < 0 || index >= size`), return `null` (line 2).
2. If `index` is `0`, invoke `removeFirst()` to remove the first node (line 3).
3. If `index` is `size - 1`, invoke `removeLast()` to remove the last node (line 4).
4. Otherwise, locate the node at the specified `index`. Let `current` denote this node and `previous` denote the node before this node, as shown in Figure 24.17a. Assign `current.next` to `previous.next` to eliminate the current node, as shown in Figure 24.17b.



(a) Before the node is deleted.

(b) After the node is deleted.

FIGURE 24.17 A node is deleted from the list.

Listing 24.6 gives the implementation of `MyLinkedList`. The implementation of `get(index)`, `indexOf(e)`, `lastIndexOf(e)`, `contains(e)`, and `set(index, e)` is omitted and left as an exercise. The `iterator()` method defined in the `java.lang.Iterable` interface is implemented to return an instance on `java.util.Iterator` (lines 126–128). The `LinkedListIterator` class implements `Iterator` with concrete methods for `hasNext`,

iterator

next, and **remove** (lines 134–149). This implementation uses **current** to point to the current position of the element being traversed (line 132). Initially, **current** points to the head of the list.

Listing 24.6 MyLinkedList.java

head, tail
no-arg constructor
constructor
getFirst
getLast
addFirst
addLast
add
removeFirst

```
 1 public class MyLinkedList<E> extends MyAbstractList<E> {
 2   private Node<E> head, tail;
 3
 4   /** Create a default list */
 5   public MyLinkedList() {
 6   }
 7
 8   /** Create a list from an array of objects */
 9   public MyLinkedList(E[] objects) {
10     super(objects);
11   }
12
13   /** Return the head element in the list */
14   public E getFirst() {
15     if (size == 0) {
16       return null;
17     }
18     else {
19       return head.element;
20     }
21   }
22
23   /** Return the last element in the list */
24   public E getLast() {
25     if (size == 0) {
26       return null;
27     }
28     else {
29       return tail.element;
30     }
31   }
32
33   /** Add an element to the beginning of the list */
34   public void addFirst(E e) {
35     // Implemented in Section 24.4.3.1, so omitted here
36   }
37
38   /** Add an element to the end of the list */
39   public void addLast(E e) {
40     // Implemented in Section 24.4.3.2, so omitted here
41   }
42
43   @Override /** Add a new element at the specified index
44    * in this list. The index of the head element is 0 */
45   public void add(int index, E e) {
46     // Implemented in Section 24.4.3.3, so omitted here
47   }
48
49   /** Remove the head node and
50    *  return the object that is contained in the removed node. */
51   public E removeFirst() {
52     // Implemented in Section 24.4.3.4, so omitted here
53   }
54
```

```java
  /** Remove the last node and
   * return the object that is contained in the removed node. */
  public E removeLast() {
    // Implemented in Section 24.4.3.5, so omitted here
  }

  @Override /** Remove the element at the specified position in this
   *  list. Return the element that was removed from the list. */
  public E remove(int index) {
    // Implemented earlier in Section 24.4.3.6, so omitted here
  }

  @Override
  public String toString() {
    StringBuilder result = new StringBuilder("[");

    Node<E> current = head;
    for (int i = 0; i < size; i++) {
      result.append(current.element);
      current = current.next;
      if (current != null) {
        result.append(", "); // Separate two elements with a comma
      }
      else {
        result.append("]"); // Insert the closing ] in the string
      }
    }

    return result.toString();
  }

  @Override /** Clear the list */
  public void clear() {
    size = 0;
    head = tail = null;
  }

  @Override /** Return true if this list contains the element e */
  public boolean contains(E e) {
    System.out.println("Implementation left as an exercise");
    return true;
  }

  @Override /** Return the element at the specified index */
  public E get(int index) {
    System.out.println("Implementation left as an exercise");
    return null;
  }

  @Override /** Return the index of the head matching element
   *  in this list. Return -1 if no match. */
  public int indexOf(E e) {
    System.out.println("Implementation left as an exercise");
    return 0;
  }

  @Override /** Return the index of the last matching element
   *  in this list. Return -1 if no match. */
  public int lastIndexOf(E e) {
    System.out.println("Implementation left as an exercise");
```

removeLast

remove

toString

clear

contains

get

indexOf

lastIndexOf

set
iterator
LinkedListIterator class
Node inner class

```
      return 0;
    }

    @Override /** Replace the element at the specified position
     * in this list with the specified element. */
    public E set(int index, E e) {
      System.out.println("Implementation left as an exercise");
      return null;
    }

    @Override /** Override iterator() defined in Iterable */
    public java.util.Iterator<E> iterator() {
      return new LinkedListIterator();
    }

    private class LinkedListIterator
        implements java.util.Iterator<E> {
      private Node<E> current = head; // Current index

      @Override
      public boolean hasNext() {
        return (current != null);
      }

      @Override
      public E next() {
        E e = current.element;
        current = current.next;
        return e;
      }

      @Override
      public void remove() {
        System.out.println("Implementation left as an exercise");
      }
    }

    // This class is only used in LinkedList, so it is private.
    // This class does not need to access any
    // instance members of LinkedList, so it is defined static.
    private static class Node<E> {
      E element;
      Node<E> next;

      public Node(E element) {
        this.element = element;
      }
    }
  }
```

24.4.4 MyArrayList vs. MyLinkedList

Both `MyArrayList` and `MyLinkedList` can be used to store a list. `MyArrayList` is implemented using an array and `MyLinkedList` is implemented using a linked list. The overhead of `MyArrayList` is smaller than that of `MyLinkedList`. However, `MyLinkedList` is more efficient if you need to insert elements into and delete elements from the beginning of the list. Table 24.1 summarizes the complexity of the methods in `MyArrayList` and `MyLinkedList`. Note that `MyArrayList` is the same as `java.util.ArrayList` and `MyLinkedList` is the same as `java.util.LinkedList`.

TABLE 24.1 Time Complexities for Methods in `MyArrayList` and `MyLinkedList`

Methods	*MyArrayList/ArrayList*	*MyLinkedList/LinkedList*
`add(e: E)`	$O(1)$	$O(1)$
`add(index: int, e: E)`	$O(n)$	$O(n)$
`clear()`	$O(1)$	$O(1)$
`contains(e: E)`	$O(n)$	$O(n)$
`get(index: int)`	$O(1)$	$O(n)$
`indexOf(e: E)`	$O(n)$	$O(n)$
`isEmpty()`	$O(1)$	$O(1)$
`lastIndexOf(e: E)`	$O(n)$	$O(n)$
`remove(e: E)`	$O(n)$	$O(n)$
`size()`	$O(1)$	$O(1)$
`remove(index: int)`	$O(n)$	$O(n)$
`set(index: int, e: E)`	$O(n)$	$O(n)$
`addFirst(e: E)`	$O(n)$	$O(1)$
`removeFirst()`	$O(n)$	$O(1)$

24.4.5 Variations of Linked Lists

The linked list introduced in the preceding sections is known as a *singly linked list*. It contains a pointer to the list's first node, and each node contains a pointer to the next node sequentially. Several variations of the linked list are useful in certain applications.

A *circular, singly linked list* is like a singly linked list, except that the pointer of the last node points back to the first node, as shown in Figure 24.18a. Note that `tail` is not needed for circular linked lists. `head` points to the current node in the list. Insertion and deletion take place at the current node. A good application of a circular linked list is in the operating system that serves multiple users in a timesharing fashion. The system picks a user from a circular list and grants a small amount of CPU time, then moves on to the next user in the list.

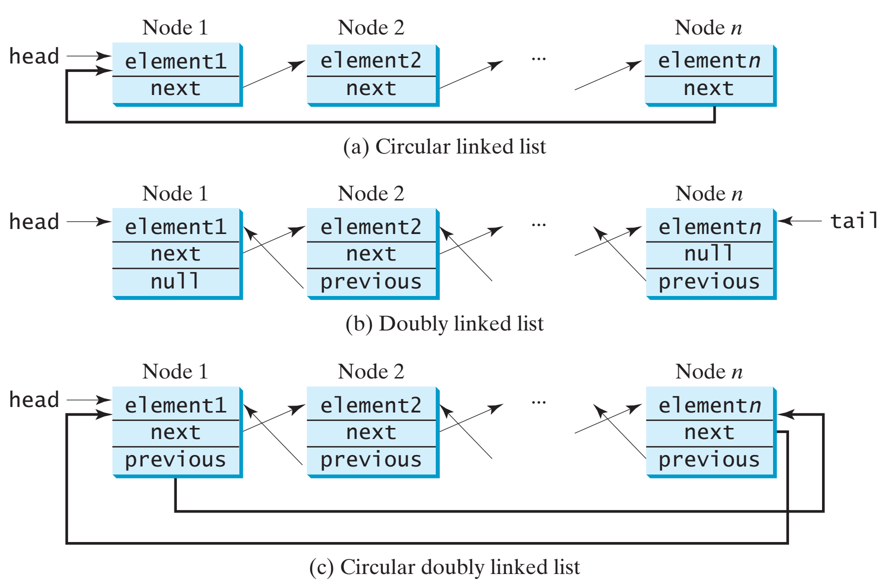


FIGURE 24.18 Linked lists may appear in various forms.

A *doubly linked list* contains nodes with two pointers. One points to the next node and the other to the previous node, as shown in Figure 24.18b. These two pointers are conveniently called *a forward pointer* and *a backward pointer*. Thus, a doubly linked list can be traversed forward and backward. The `java.util.LinkedList` class is implemented using a doubly linked list, and it supports traversing of the list forward and backward using the `ListIterator`.

A *circular*, *doubly linked list* is like a doubly linked list, except that the forward pointer of the last node points to the first node and the backward pointer of the first pointer points to the last node, as shown in Figure 24.18c.

The implementations of these linked lists are left as exercises.

Check Point

24.12 Both `MyArrayList` and `MyLinkedList` are used to store a list of objects. Why do we need both types of lists?

24.13 Draw a diagram to show the linked list after each of the following statements is executed.

```
MyLinkedList<Double> list = new MyLinkedList<>();
list.add(1.5);
list.add(6.2);
list.add(3.4);
list.add(7.4);
list.remove(1.5);
list.remove(2);
```

24.14 What is the time complexity of the `addFirst(e)` and `removeFirst()` methods in `MyLinkedList`?

24.15 Suppose you need to store a list of elements. If the number of elements in the program is fixed, what data structure should you use? If the number of elements in the program changes, what data structure should you use?

24.16 If you have to add or delete the elements at the beginning of a list, should you use `MyArrayList` or `MyLinkedList`? If most of the operations on a list involve retrieving an element at a given index, should you use `MyArrayList` or `MyLinkedList`?

24.17 Simplify the code in lines 75-80 in Listing 24.6 using a conditional expression.

24.5 Stacks and Queues

Key Point

Stacks can be implemented using array lists and queues can be implemented using linked lists.

A stack can be viewed as a special type of list whose elements are accessed, inserted, and deleted only from the end (top), as shown in Figure 10.11. A queue represents a waiting list. It can be viewed as a special type of list whose elements are inserted into the end (tail) of the queue, and are accessed and deleted from the beginning (head), as shown in Figure 24.19.

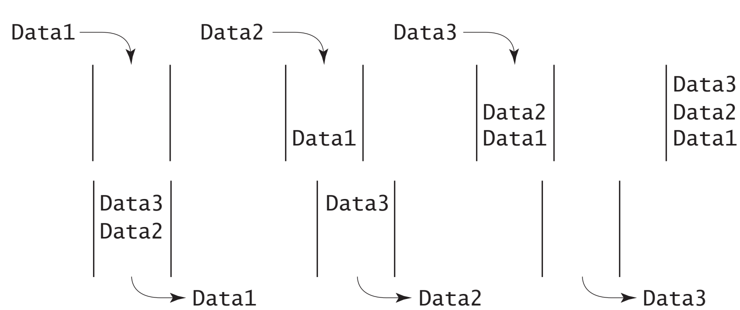
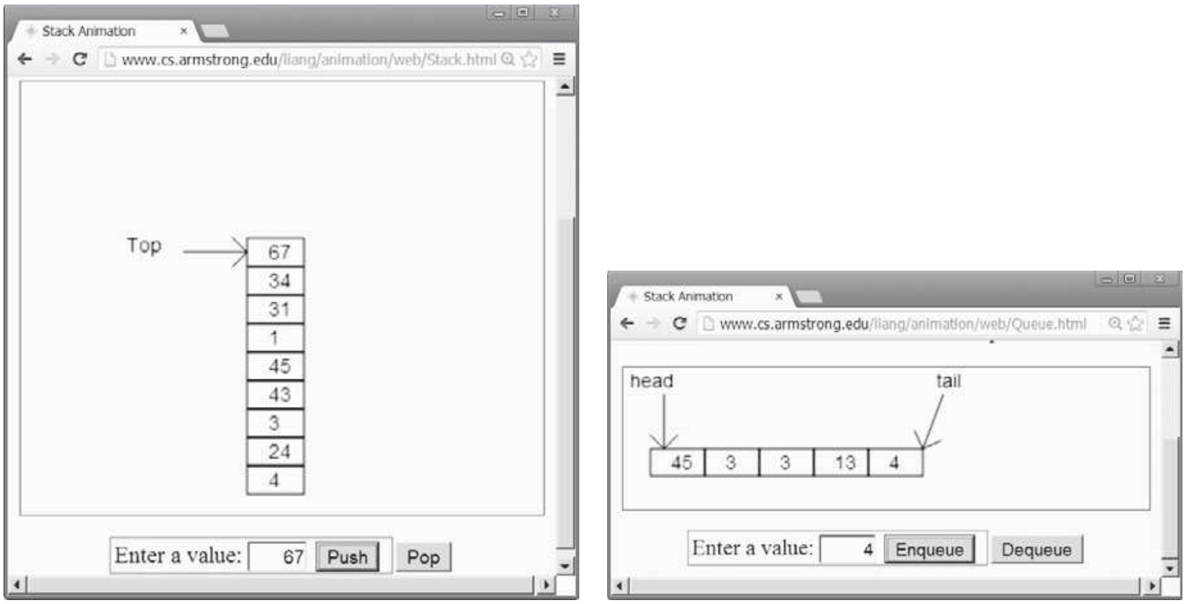


FIGURE 24.19 A queue holds objects in a first-in, first-out fashion.

Pedagogical Note

For an interactive demo on how stacks and queues work, go to www.cs.armstrong.edu/liang/animation/web/Stack.html, and www.cs.armstrong.edu/liang/animation/web/Queue.html, as shown in Figure 24.20.

stack and queue animation on Companion Website



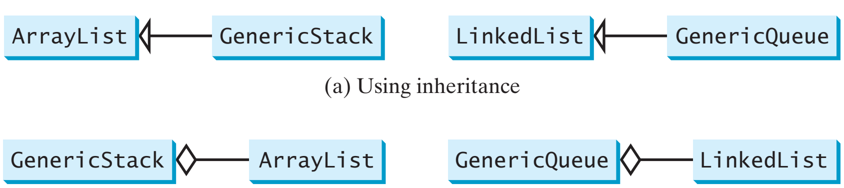
(a) Stack animation (b) Queue animation

FIGURE 24.20 The animation tool enables you to see how stacks and queues work.

Since the insertion and deletion operations on a stack are made only at the end of the stack, it is more efficient to implement a stack with an array list than a linked list. Since deletions are made at the beginning of the list, it is more efficient to implement a queue using a linked list than an array list. This section implements a stack class using an array list and a queue class using a linked list.

There are two ways to design the stack and queue classes:

- Using inheritance: You can define a stack class by extending `ArrayList`, and a queue class by extending `LinkedList`, as shown in Figure 24.21a. (inheritance)
- Using composition: You can define an array list as a data field in the stack class, and a linked list as a data field in the queue class, as shown in Figure 24.21b. (composition)



(a) Using inheritance

(b) Using composition

FIGURE 24.21 `GenericStack` and `GenericQueue` may be implemented using inheritance or composition.

Both designs are fine, but using composition is better because it enables you to define a completely new stack class and queue class without inheriting the unnecessary and inappropriate methods from the array list and linked list. The implementation of the stack class using the composition approach was given in Listing 19.1, GenericStack.java. Listing 24.7 implements the `GenericQueue` class using the composition approach. Figure 24.22 shows the UML of the class.

GenericQueue<E>	
-list: java.util.LinkedList<E>	
+enqueue(e: E): void	Adds an element to this queue.
+dequeue(): E	Removes an element from this queue.
+getSize(): int	Returns the number of elements in this queue.

FIGURE 24.22 **GenericQueue** uses a linked list to provide a first-in, first-out data structure.

LISTING 24.7 GenericQueue.java

linked list

enqueue

dequeue

getSize

toString

```
1  public class GenericQueue<E> {
2    private java.util.LinkedList<E> list
3      = new java.util.LinkedList<>();
4
5    public void enqueue(E e) {
6      list.addLast(e);
7    }
8
9    public E dequeue() {
10     return list.removeFirst();
11   }
12
13   public int getSize() {
14     return list.size();
15   }
16
17   @Override
18   public String toString() {
19     return "Queue: " + list.toString();
20   }
21 }
```

A linked list is created to store the elements in a queue (lines 2–3). The **enqueue(e)** method (lines 5–7) adds element **e** into the tail of the queue. The **dequeue()** method (lines 9–11) removes an element from the head of the queue and returns the removed element. The **getSize()** method (lines 13–15) returns the number of elements in the queue.

Listing 24.8 gives an example that creates a stack using **GenericStack** and a queue using **GenericQueue**. It uses the **push** (**enqueue**) method to add strings to the stack (queue) and the **pop** (**dequeue**) method to remove strings from the stack (queue).

LISTING 24.8 TestStackQueue.java

```
public class TestStackQueue {
  public static void main(String[] args) {
    // Create a stack
    GenericStack<String> stack =
      new GenericStack<>();

    // Add elements to the stack
    stack.push("Tom"); // Push it to the stack
    System.out.println("(1) " + stack);

    stack.push("Susan"); // Push it to the the stack
    System.out.println("(2) " + stack);

    stack.push("Kim"); // Push it to the stack
    stack.push("Michael"); // Push it to the stack
    System.out.println("(3) " + stack);

```

```java
    // Remove elements from the stack
    System.out.println("(4) " + stack.pop());
    System.out.println("(5) " + stack.pop());
    System.out.println("(6) " + stack);

    // Create a queue
    GenericQueue<String> queue = new GenericQueue<>();

    // Add elements to the queue
    queue.enqueue("Tom"); // Add it to the queue
    System.out.println("(7) " + queue);

    queue.enqueue("Susan"); // Add it to the queue
    System.out.println("(8) " + queue);

    queue.enqueue("Kim"); // Add it to the queue
    queue.enqueue("Michael"); // Add it to the queue
    System.out.println("(9) " + queue);

    // Remove elements from the queue
    System.out.println("(10) " + queue.dequeue());
    System.out.println("(11) " + queue.dequeue());
    System.out.println("(12) " + queue);
  }
}
```

```
(1) stack: [Tom]
(2) stack: [Tom, Susan]
(3) stack: [Tom, Susan, Kim, Michael]
(4) Michael
(5) Kim
(6) stack: [Tom, Susan]
(7) Queue: [Tom]
(8) Queue: [Tom, Susan]
(9) Queue: [Tom, Susan, Kim, Michael]
(10) Tom
(11) Susan
(12) Queue: [Kim, Michael]
```

stack time complexity

For a stack, the **push(e)** method adds an element to the top of the stack, and the **pop()** method removes the top element from the stack and returns the removed element. It is easy to see that the time complexity for the **push** and **pop** methods is $O(1)$.

queue time complexity

For a queue, the **enqueue(e)** method adds an element to the tail of the queue, and the **dequeue()** method removes the element from the head of the queue. It is easy to see that the time complexity for the **enqueue** and **dequeue** methods is $O(1)$.

Check Point

24.18 You can use inheritance or composition to design the data structures for stacks and queues. Discuss the pros and cons of these two approaches.

24.19 If **LinkedList** is replaced by **ArrayList** in lines 2–3 in Listing 24.7 GenericQueue.java, what will be the time complexity for the **enqueue** and **dequeue** methods?

24.20 Which lines of the following code are wrong?

```java
1 List<String> list = new ArrayList<>();
2 list.add("Tom");
3 list = new LinkedList<>();
4 list.add("Tom");
5 list = new GenericStack<>();
6 list.add("Tom");
```

24.6 Priority Queues

Key Point

Priority queues can be implemented using heaps.

An ordinary queue is a first-in, first-out data structure. Elements are appended to the end of the queue and removed from the beginning. In a *priority queue*, elements are assigned with priorities. When accessing elements, the element with the highest priority is removed first. For example, the emergency room in a hospital assigns priority numbers to patients; the patient with the highest priority is treated first.

A priority queue can be implemented using a heap, in which the root is the object with the highest priority in the queue. Heaps were introduced in Section 23.6, Heap Sort. The class diagram for the priority queue is shown in Figure 24.23. Its implementation is given in Listing 24.9.

MyPriorityQueue <E extends Comparable<E>>	
-heap: Heap<E>	
+enqueue(element: E): void	Adds an element to this queue.
+dequeue(): E	Removes an element from this queue.
+getSize(): int	Returns the number of elements in this queue.

FIGURE 24.23 `MyPriorityQueue` uses a heap to provide a largest-in, first-out data structure.

LISTING 24.9 MyPriorityQueue.java

heap for priority queue
enqueue
dequeue
getsize

```
public class MyPriorityQueue<E extends Comparable<E>> {
  private Heap<E> heap = new Heap<>();

  public void enqueue(E newObject) {
    heap.add(newObject);
  }

  public E dequeue() {
    return heap.remove();
  }

  public int getSize() {
    return heap.getSize();
  }
}
```

Listing 24.10 gives an example of using a priority queue for patients. The `Patient` class is defined in lines 19–37. Four patients are created with associated priority values in lines 3–6. Line 8 creates a priority queue. The patients are enqueued in lines 10–13. Line 16 dequeues a patient from the queue.

LISTING 24.10 TestPriorityQueue.java

create a patient
create a priority queue
add to queue

```
1  public class TestPriorityQueue {
2    public static void main(String[] args) {
3      Patient patient1 = new Patient("John", 2);
4      Patient patient2 = new Patient("Jim", 1);
5      Patient patient3 = new Patient("Tim", 5);
6      Patient patient4 = new Patient("Cindy", 7);
7
8      MyPriorityQueue<Patient> priorityQueue
9        = new MyPriorityQueue<>();
10     priorityQueue.enqueue(patient1);
11     priorityQueue.enqueue(patient2);
```

```java
    priorityQueue.enqueue(patient3);
    priorityQueue.enqueue(patient4);

    while (priorityQueue.getSize() > 0)
      System.out.print(priorityQueue.dequeue() + " ");
  }

  static class Patient implements Comparable<Patient> {
    private String name;
    private int priority;

    public Patient(String name, int priority) {
      this.name = name;
      this.priority = priority;
    }

    @Override
    public String toString() {
      return name + "(priority:" + priority + ")";
    }

    @Override
    public int compareTo(Patient patient) {
      return this.priority - patient.priority;
    }
  }
}
```

remove from queue

inner class `Patient`

`compareTo`

```
Cindy(priority:7) Tim(priority:5) John(priority:2) Jim(priority:1)
```

Check Point

24.21 What is a priority queue?

24.22 What are the time complexity of the `enqueue`, `dequeue` , and `getSize` methods in `MyProrityQueue`?

24.23 Which of the following statements are wrong?

```java
1 MyPriorityQueue<Object> q1 = new MyPriorityQueue<>();
2 MyPriorityQueue<Number> q2 = new MyPriorityQueue<>();
3 MyPriorityQueue<Integer> q3 = new MyPriorityQueue<>();
4 MyPriorityQueue<Date> q4 = new MyPriorityQueue<>();
5 MyPriorityQueue<String> q5 = new MyPriorityQueue<>();
```

Chapter Summary

1. You learned how to implement array lists, linked lists, stacks, and queues.

2. To define a data structure is essentially to define a class. The class for a data structure should use data fields to store data and provide methods to support operations such as insertion and deletion.

3. To create a data structure is to create an instance from the class. You can then apply the methods on the instance to manipulate the data structure, such as inserting an element into the data structure or deleting an element from the data structure.

4. You learned how to implement a priority queue using a heap.

Quiz

Answer the quiz for this chapter online at www.cs.armstrong.edu/liang/intro10e/test.html.

MyProgrammingLab™

Programming Exercises

24.1 (*Add set operations in* `MyList`) Define the following methods in `MyList` and implement them in `MyAbstractList`:

```
/** Adds the elements in otherList to this list.
  * Returns true if this list changed as a result of the call */
public boolean addAll(MyList<E> otherList);

/** Removes all the elements in otherList from this list
  * Returns true if this list changed as a result of the call */
public boolean removeAll(MyList<E> otherList);

/** Retains the elements in this list that are also in otherList
  * Returns true if this list changed as a result of the call */
public boolean retainAll(MyList<E> otherList);
```

Write a test program that creates two `MyArrayList`s, `list1` and `list2`, with the initial values `{"Tom", "George", "Peter", "Jean", "Jane"}` and `{"Tom", "George", "Michael", "Michelle", "Daniel"}`, then perform the following operations:

- Invokes `list1.addAll(list2)`, and displays `list1` and `list2`.
- Recreates `list1` and `list2` with the same initial values, invokes `list1.removeAll(list2)`, and displays `list1` and `list2`.
- Recreates `list1` and `list2` with the same initial values, invokes `list1.retainAll(list2)`, and displays `list1` and `list2`.

***24.2** (*Implement* `MyLinkedList`) The implementations of the methods `contains(E e)`, `get(int index)`, `indexOf(E e)`, `lastIndexOf(E e)`, and `set(int index, E e)` are omitted in the text. Implement these methods.

***24.3** (*Implement a doubly linked list*) The `MyLinkedList` class used in Listing 24.6 is a one-way directional linked list that enables one-way traversal of the list. Modify the `Node` class to add the new data field name `previous` to refer to the previous node in the list, as follows:

```
public class Node<E> {
  E element;
  Node<E> next;
  Node<E> previous;

  public Node(E e) {
    element = e;
  }
}
```

Implement a new class named `TwoWayLinkedList` that uses a doubly linked list to store elements. The `MyLinkedList` class in the text extends `MyAbstractList`. Define `TwoWayLinkedList` to extend the `java.util.AbstractSequentialList` class. You need to implement all the methods defined in `MyLinkedList` as well as the methods `listIterator()`

and `listIterator(int index)`. Both return an instance of `java.util.ListIterator<E>`. The former sets the cursor to the head of the list and the latter to the element at the specified index.

24.4 (*Use the* ***`GenericStack`*** *class*) Write a program that displays the first 50 prime numbers in descending order. Use a stack to store the prime numbers.

24.5 (*Implement* ***`GenericQueue`*** *using inheritance*) In Section 24.5, Stacks and Queues, `GenericQueue` is implemented using composition. Define a new queue class that extends `java.util.LinkedList`.

24.6** (*Generic* ***`PriorityQueue` using `Comparator`) Revise `MyPriorityQueue` in Listing 24.9, using a generic parameter for comparing objects. Define a new constructor with a `Comparator` as its argument as follows:

```
PriorityQueue(Comparator<? super E> comparator)
```

****24.7** (*Animation: linked list*) Write a program to animate search, insertion, and deletion in a linked list, as shown in Figure 24.1b. The *Search* button searches the specified value in the list. The *Delete* button deletes the specified value from the list. The *Insert* button appends the value into the list if the index is not specified; otherwise, it inserts the value into the specified index in the list.

***24.8** (*Animation: array list*) Write a program to animate search, insertion, and deletion in an array list, as shown in Figure 24.1a. The *Search* button searches the specified value in the list. The *Delete* button deletes the specified value from the list. The *Insert* button appends the value into the list if the index is not specified; otherwise, it inserts the value into the specified index in the list.

***24.9** (*Animation: array list in slow motion*) Improve the animation in the preceding programming exercise by showing the insertion and deletion operations in a slow motion, as shown at http://www.cs.armstrong.edu/liang/animation/ArrayListAnimationInSlowMotion.html.

***24.10** (*Animation: stack*) Write a program to animate push and pop in a stack, as shown in Figure 24.20a.

***24.11** (*Animation: doubly linked list*) Write a program to animate search, insertion, and deletion in a doubly linked list, as shown in Figure 24.24. The *Search* button searches the specified value in the list. The *Delete* button deletes the specified value from the list. The *Insert* button appends the value into the list if the index is not specified; otherwise, it inserts the value into the specified index in the list. Also add two buttons named *Forward Traversal* and *Backward Traversal* for displaying the elements in a forward and backward order, respectively, using iterators.

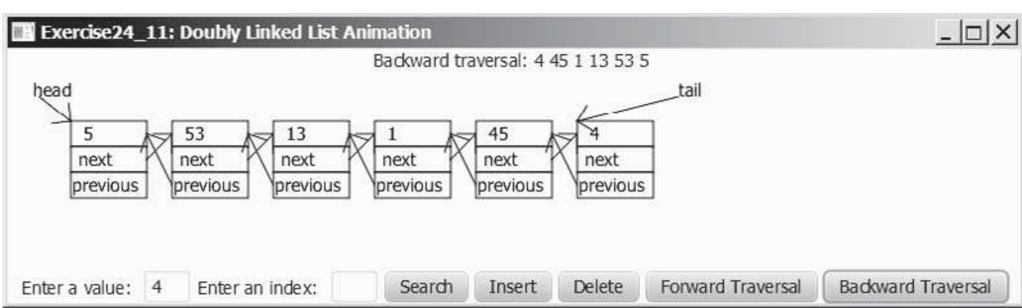


FIGURE 24.24 The program animates the work of a doubly linked list.

***24.12** (*Animation: queue*) Write a program to animate the **enqueue** and **dequeue** operations on a queue, as shown in Figure 24.20b.

***24.13** (*Fibonacci number iterator*) Define an iterator class named **FibonacciIterator** for iterating Fibonacci numbers. The constructor takes an argument that specifies the limit of the maximum Fibonacci number. For example, new **FibonacciIterator(23302)** creates an iterator that iterates Fibonacci numbers less than or equal to **23302**. Write a test program that uses this iterator to display all Fibonacci numbers less than or equal to **100000**.

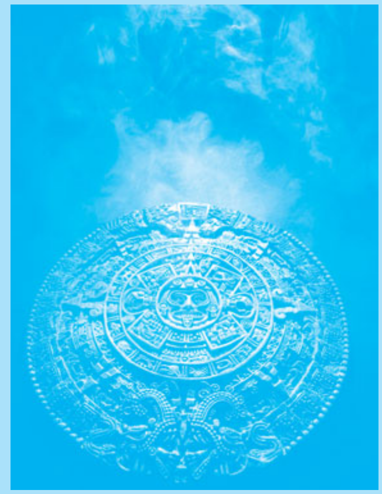
***24.14** (*Prime number iterator*) Define an iterator class named **PrimeIterator** for iterating prime numbers. The constructor takes an argument that specifies the limit of the maximum prime number. For example, new **PrimeIterator(23302)** creates an iterator that iterates prime numbers less than or equal to **23302**. Write a test program that uses this iterator to display all prime numbers less than or equal to **100000**.

****24.15** (*Test* **MyArrayList**) Design and write a complete test program to test if the **MyArrayList** class in Listing 24.3 meets all requirements.

****24.16** (*Test* **MyLinkedList**) Design and write a complete test program to test if the **MyLinkedList** class in Listing 24.6 meets all requirements.

CHAPTER

25



BINARY SEARCH TREES

Objectives

- To design and implement a binary search tree (§25.2).
- To represent binary trees using linked data structures (§25.2.1).
- To search an element in a binary search tree (§25.2.2).
- To insert an element into a binary search tree (§25.2.3).
- To traverse elements in a binary tree (§25.2.4).
- To design and implement the `Tree` interface, `AbstractTree` class, and the `BST` class (§25.2.5).
- To delete elements from a binary search tree (§25.3).
- To display a binary tree graphically (§25.4).
- To create iterators for traversing a binary tree (§25.5).
- To implement Huffman coding for compressing data using a binary tree (§25.6).