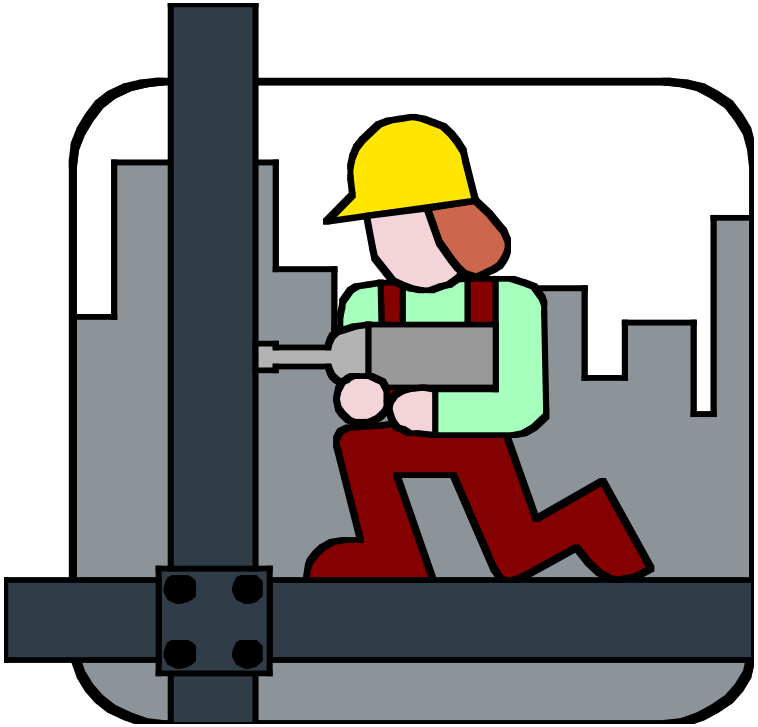
Implementations I



Agenda

- **Inner classes and implementation of `ArrayList`**
  - Nested classes and inner classes
  - The `AbstractCollection` class
  - Implementation of `ArrayList`
- **Stack and queues**
  - Array-based implementations
  - Linked list-based implementations
- **Linked lists**
  - Doubly linked lists

Iterator design using nested class

figure 15.5

Iterator design using nested class

```
1  package weiss.ds;
2
3  public class MyContainer
4  {
5      private Object [ ] items;
6      private int size = 0;
7      // Other methods for MyContainer not shown
8
9      public Iterator iterator( )
10       { return new LocalIterator( this ); }
11
12     // The iterator class as a nested class
13     private static class LocalIterator implements Iterator
14     {
15         private int current = 0;
16         private MyContainer container;
17
18         private LocalIterator( MyContainer c )
19           { container = c; }
20
21         public boolean hasNext( )
22           { return current < container.size; }
23
24         public Object next( )
25           { return container.items[ current++ ]; }
26     }
27 }
```

Notice the `static` specification

Iterator design using inner class

figure 15.8

Iterator design using inner class

```
1  package weiss.ds;
2
3  public class MyContainer
4  {
5      private Object [ ] items;
6      private int size = 0;
7
8      // Other methods for MyContainer not shown
9
10     public Iterator iterator( )
11       { return new LocalIterator( ); }
12
13     // The iterator class as an inner class
14     private class LocalIterator implements Iterator
15     {
16         private int current = 0;
17
18         public boolean hasNext( )
19           { return current < MyContainer.this.size; }
20
21         public Object next( )
22           { return MyContainer.this.items[ current++ ]; }
23     }
24 }
```

```
1       // The iterator class as an inner class
2       private class LocalIterator implements Iterator
3       {
4           private int current = 0;
5
6           public boolean hasNext( )
7             { return current < size; }
8
9           public Object next( )
10            { return items[ current++ ]; }
11      }
```

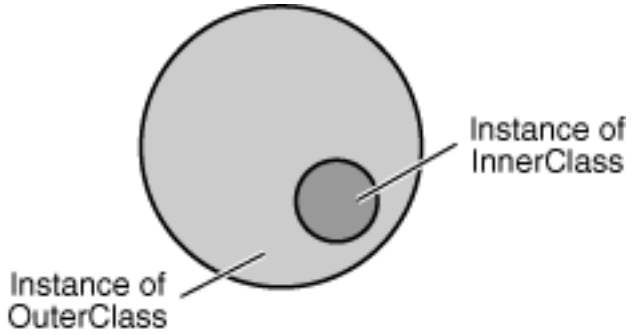
figure 15.9

Inner class; `Outer.this` may be optional.

Nested classes and inner classes

A **static nested class** interacts with the instance members of its outer class (and other classes) just like any other top-level class. In effect, a static nested class is behaviorally a top-level class that has been nested in another top-level class for packaging convenience.

As with instance methods and variables, an **inner class** is associated with an instance of its enclosing class and has direct access to that object's methods and fields.



Abstract collections

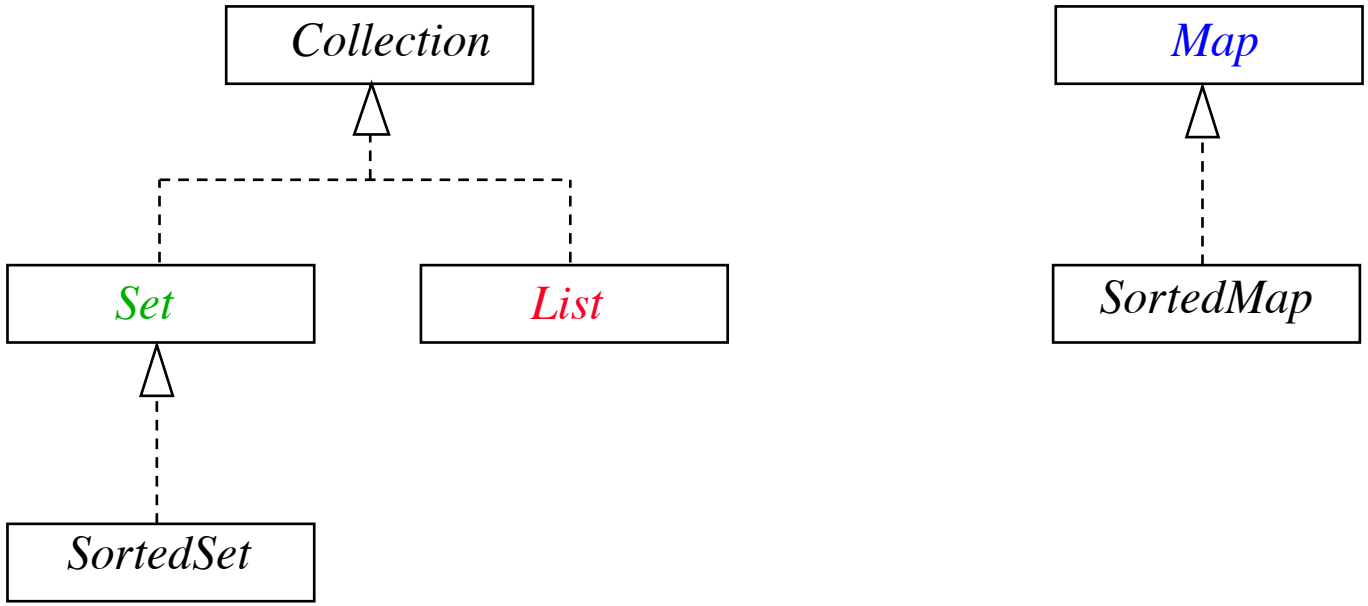
A **set** is an unordered collection of elements. No duplicates are allowed.

A **list** is an ordered collection of elements. Duplicates are allowed. Lists are also known an *sequences*.

A map is an unordered collection of key-value pairs. The keys must be unique. Maps are also known as *dictionaries*.

Interfaces for collections

java.util.*



interface **Collection<E>**

```
boolean add(E o)
boolean addAll(Collection<? extends E> c)
void clear()
boolean contains(Object o)
boolean containsAll(Collection<?> c)
boolean isEmpty()
Iterator<E> iterator()
boolean remove(Object o)
boolean removeAll(Collection<?> c)
boolean retainAll(Collection<?> c)
int size()
Object[] toArray()
<T> T[] toArray(T[] a)
```

```
1  package weiss.util;
2
3  /**
4   * AbstractCollection provides default implementations for
5   * some of the easy methods in the Collection interface.
6   */
7  public abstract class AbstractCollection<AnyType> implements Collection<AnyType>
8  {
9      /**
10      * Tests if this collection is empty.
11      * @return true if the size of this collection is zero.
12      */
13     public boolean isEmpty( )
14     {
15         return size( ) == 0;
16     }
17
18     /**
19      * Change the size of this collection to zero.
20      */
21     public void clear( )
22     {
23         Iterator<AnyType> itr = iterator( );
24         while( itr.hasNext( ) )
25         {
26             itr.next( );
27             itr.remove( );
28         }
29     }
30
31     /**
32      * Adds x to this collections.
33      * This default implementation always throws an exception.
34      * @param x the item to add.
35      * @throws UnsupportedOperationException always.
36      */
37     public boolean add( AnyType x )
38     {
39         throw new UnsupportedOperationException( );
40     }
```

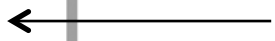


figure 15.10

Sample implementation of `AbstractCollection` (part 1) of 3

figure 15.11

Sample implementation of `AbstractCollection` (part 2)

```
41      /**
42       * Returns true if this collection contains x.
43       * If x is null, returns false.
44       * (This behavior may not always be appropriate.)
45       * @param x the item to search for.
46       * @return true if x is not null and is found in
47       * this collection.
48       */
49      public boolean contains( Object x )
50      {
51          if( x == null )
52              return false;
53
54          for( AnyType val : this )
55              if( x.equals( val ) )
56                  return true;
57
58          return false;
59      }
60
61      /**
62       * Removes non-null x from this collection.
63       * (This behavior may not always be appropriate.)
64       * @param x the item to remove.
65       * @return true if remove succeeds.
66       */
67      public boolean remove( Object x )
68      {
69          if( x == null )
70              return false;
71
72          Iterator itr = iterator( );
73          while( itr.hasNext( ) )
74              if( x.equals( itr.next( ) ) )
75              {
76                  itr.remove( );
77                  return true;
78              }
79
80          return false;
81      }
```

```
82      /**
83       * Obtains a primitive array view of the collection.
84       * @return the primitive array view.
85       */
86      public Object [ ] toArray( )
87      {
88          Object [ ] copy = new Object[ size( ) ];
89          int i = 0;
90
91          for( AnyType val : this )
92              copy[ i++ ] = val;
93
94          return copy;
95      }
96
97      public <OtherType> OtherType [ ] toArray( OtherType [ ] arr )
98      {
99          int theSize = size( );
100
101         if( arr.length < theSize )
102             arr = ( OtherType [ ] ) java.lang.reflect.Array.newInstance(
103                         arr.getClass( ).getComponentType( ), theSize );
104         else if( theSize < arr.length )
105             arr[ theSize ] = null;
106
107         Object [ ] copy = arr;
108         int i = 0;
109
110         for( AnyType val : this )
111             copy[ i++ ] = val;
112
113         return copy;
114     }
115
116     /**
117      * Return a string representation of this collection.
118      */
119     public String toString( )
120     {
121         StringBuilder result = new StringBuilder( "[ " );
122
123         for( AnyType obj : this )
124             result.append( obj + " " );
125
126         result.append( "]" );
127
128         return result.toString( );
129     }
130 }
```

figure 15.12

Sample implementation of `AbstractCollection` (part 3)

Flaw

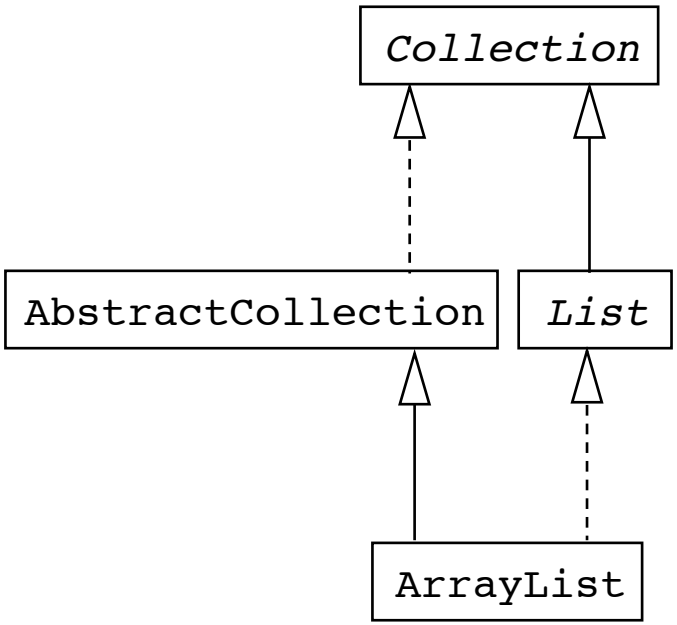
A Collection may contain itself!

`toString` as implemented in `java.util.AbstractCollection`

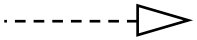
```
public String toString() {
    Iterator<E> it = iterator();
    if (!it.hasNext())
        return "[]";
    StringBuilder sb = new StringBuilder();
    sb.append('[');
    for (;;) {
        E e = it.next();
        sb.append(e == this ? "(this Collection)" : e);
        if (!it.hasNext())
            return sb.append(']').toString();
        sb.append(',').append(' ');
    }
}
```

ArrayList

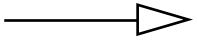
An array list (`ArrayList`) is a list that uses an array to store its elements.



italic: interface
normal: class



implements



extends

figure 15.13

ArrayList implementation (part 1) of 3

```
1  package weiss.util;
2
3  public class ArrayList<AnyType> extends AbstractCollection<AnyType>
4                                   implements List<AnyType>
5  {
6      private static final int DEFAULT_CAPACITY = 10;
7      private static final int NOT_FOUND = -1;
8
9      private AnyType [ ] theItems;
10     private int theSize;
11     private int modCount = 0;
12
13     public ArrayList( )
14       { clear( ); }
15
16     public ArrayList( Collection<AnyType> other )
17     {
18         clear( );
19         for( AnyType obj : other )
20             add( obj );
21     }
22
23     public int size( )
24       { return theSize; }
25
26     public void clear( )
27     {
28         theSize = 0;
29         theItems = (AnyType []) new Object[ DEFAULT_CAPACITY ];
30         modCount++;
31     }
32
33     public AnyType get( int idx )
34     {
35         if( idx < 0 || idx >= size( ) )
36             throw new ArrayIndexOutOfBoundsException( );
37         return theItems[ idx ];
38     }
39
40     public AnyType set( int idx, AnyType newVal )
41     {
42         if( idx < 0 || idx >= size( ) )
43             throw new ArrayIndexOutOfBoundsException( );
44         AnyType old = theItems[ idx ];
45         theItems[ idx ] = newVal;
46
47         return old;
48     }
49
50     public boolean contains( Object x )
51       { return findPos( x ) != NOT_FOUND; }
```

`modCount` represents the number of structural modifications (adds, removes) made to the `ArrayList`.

The idea is that when an iterator is constructed, the iterator saves this value in its data member `expectedModCount`.

When any iterator operation is performed, the iterator's `expectedModCount` member is compared with the `ArrayList`'s `modCount`, and if they disagree, a `ConcurrentModificationException` is thrown.

```
52      private int findPos( Object x )
53      {
54          for( int i = 0; i < size( ); i++ )
55              if( x == null )
56              {
57                  if( theItems[ i ] == null )
58                      return i;
59              }
60              else if( x.equals( theItems[ i ] ) )
61                  return i;
62
63          return NOT_FOUND;
64      }
65
66      public boolean add( AnyType x )
67      {
68          if( theItems.length == size( ) )
69          {
70              AnyType [ ] old = theItems;
71              theItems = (AnyType []) new Object[ theItems.length * 2 + 1 ];
72              for( int i = 0; i < size( ); i++ )
73                  theItems[ i ] = old[ i ];
74          }
75          theItems[ theSize++ ] = x;
76          modCount++;
77          return true;
78      }
79
80      public boolean remove( Object x )
81      {
82          int pos = findPos( x );
83
84          if( pos == NOT_FOUND )
85              return false;
86          else
87          {
88              remove( pos );
89              return true;
90          }
91      }
92
93      public AnyType remove( int idx )
94      {
95          AnyType removedItem = theItems[ idx ];
96          for( int i = idx; i < size( ) - 1; i++ )
97              theItems[ i ] = theItems[ i + 1 ];
98          theSize--;
99          modCount++;
100         return removedItem;
101     }
```

figure 15.14

ArrayList implementation (part 2)

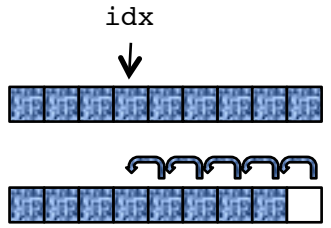


figure 15.15

ArrayList implementation (part 3)

`listIterator(int idx)`: Returns a list iterator of the elements in this list (in proper sequence), starting at the specified position in this list. The specified index indicates the first element that would be returned by an initial call to the `next` method. An initial call to the `previous` method would return the element with the specified index minus one.

```
102     public Iterator<AnyType> iterator( )
103       { return new ArrayListIterator( 0 ); }
104
105     public ListIterator<AnyType> listIterator( int idx )
106       { return new ArrayListIterator( idx ); }
107
108     // This is the implementation of the ArrayListIterator
109     private class ArrayListIterator implements ListIterator<AnyType>
110     {
111         private int current;
112         private int expectedModCount = modCount;
113         private boolean nextCompleted = false;
114         private boolean prevCompleted = false;
115
116         ArrayListIterator( int pos )
117         {
118             if( pos < 0 || pos > size( ) )
119                 throw new IndexOutOfBoundsException( );
120             current = pos;
121         }
122
123         public boolean hasNext( )
124         {
125             if( expectedModCount != modCount )
126                 throw new ConcurrentModificationException( );
127             return current < size( );
128         }
129
130         public boolean hasPrevious( )
131         {
132             if( expectedModCount != modCount )
133                 throw new ConcurrentModificationException( );
134             return current > 0;
135         }
```

```
136         public AnyType next( )
137         {
138             if( !hasNext( ) )
139                 throw new NoSuchElementException( );
140             nextCompleted = true;
141             prevCompleted = false;
142             return theItems[ current++ ];
143         }
144
145         public AnyType previous( )
146         {
147             if( !hasPrevious( ) )
148                 throw new NoSuchElementException( );
149             prevCompleted = true;
150             nextCompleted = false;
151             return theItems[ --current ];
152         }
153
154         public void remove( )
155         {
156             if( expectedModCount != modCount )
157                 throw new ConcurrentModificationException( );
158
159             if( nextCompleted )
160                 ArrayList.this.remove( --current );
161             else if( prevCompleted )
162                 ArrayList.this.remove( current );
163             else
164                 throw new IllegalStateException( );
165
166             prevCompleted = nextCompleted = false;
167             expectedModCount++;
168         }
169     }
170 }
```

figure 15.16

`ArrayList` implementation (part 4)

Does either of these proposed implementations of `clear` for `AbstractCollection` work?

```
1  public void clear( )   // Version #1
2  {
3      Iterator<AnyType> itr = iterator( );
4      while( !isEmpty( ) )
5          remove( itr.next( ) );
6  }
7
8  public void clear( )   // Version #2
9  {
10     while( !isEmpty( ) )
11         remove( iterator( ).next(  ) );
12 }
```

Proposed implementations of `clear` for `AbstractCollection`

Version #1 will throw a `ConcurrentModificationException`

Version #2 works

Does this proposed implementation of `clear` work?

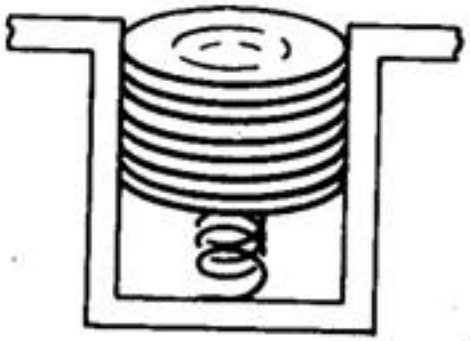
```
public void clear( )   // Version #3
{
    Iterator<AnyType> itr = iterator( );
    while( itr.hasNext( ) )
        itr.remove( );
}
```

Version #3 will throw an `IllegalStateException`

```
public void clear( )   // Version #4
{
    Iterator<AnyType> itr = iterator( );
    while( itr.hasNext( ) ) {
        itr.next( );
        itr.remove( );
    }
}
```

Version #4 works

Stacks and queues



(*a*) Stack of dishes.

(*b*) Queue waiting for a bus.

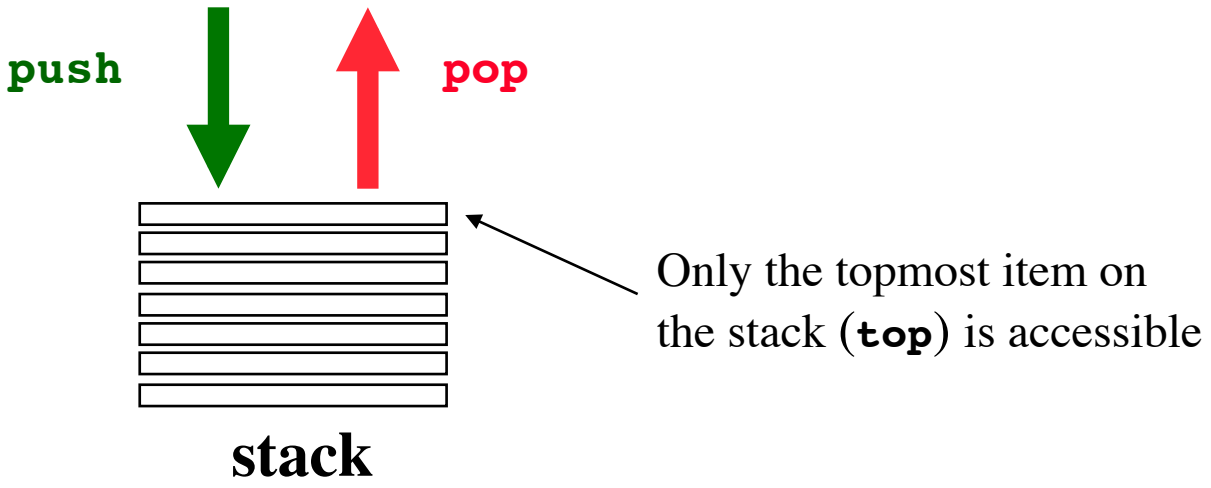
Stack

(**LIFO** = **L**ast**I**n**F**irst**O**ut)

A **stack** is a sequence of items of the same type that provides the following two operations:

`push(x)`: Add the item `x` to the top of the stack

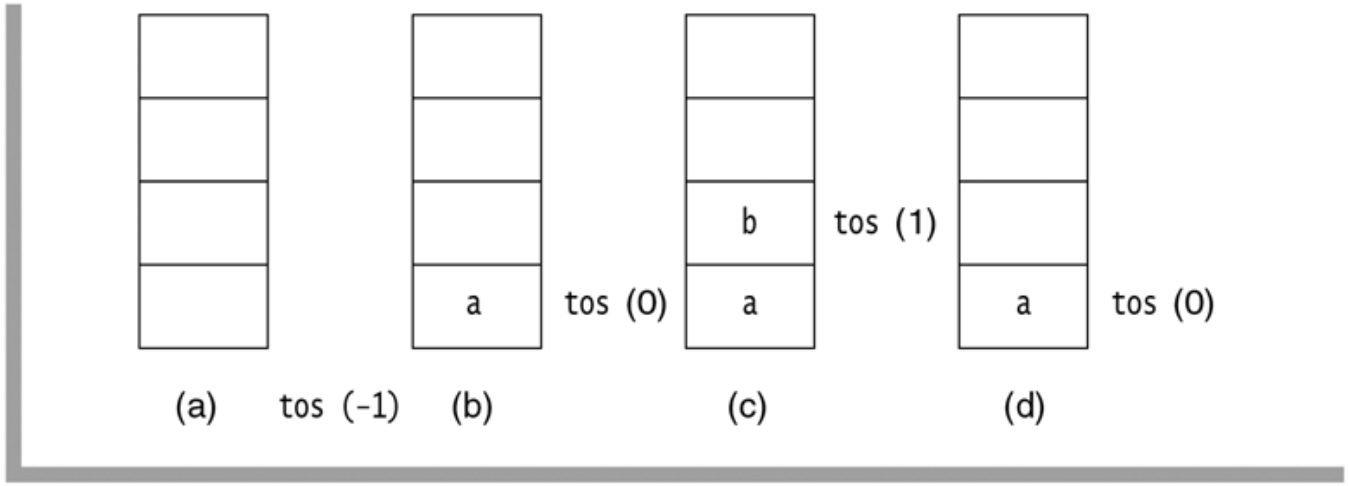
`pop`: Remove the top item from the stack



Stack implemented with an array

figure 16.1

How the stack routines work:
(a) empty stack;
(b) `push(a);`
(c) `push(b);`
(d) `pop( )`



The integer `tos` (*top of stack*) provides the array index of the top element of the stack

```
1  package weiss.nonstandard;
2
3  // ArrayStack class
4  //
5  // CONSTRUCTION: with no initializer
6  //
7  // ******************PUBLIC OPERATIONS*********************
8  // void push( x )         --> Insert x
9  // void pop( )            --> Remove most recently inserted item
10 // AnyType top( )         --> Return most recently inserted item
11 // AnyType topAndPop( )   --> Return and remove most recent item
12 // boolean isEmpty( )     --> Return true if empty; else false
13 // void makeEmpty( )      --> Remove all items
14 // ******************ERRORS********************************
15 // top, pop, or topAndPop on empty stack
16
17 public class ArrayStack<AnyType> implements Stack<AnyType>
18 {
19     public ArrayStack( )
20       { /* Figure 16.3 */ }
21
22     public boolean isEmpty( )
23       { /* Figure 16.4 */ }
24     public void makeEmpty( )
25       { /* Figure 16.4 */ }
26     public Object top( )
27       { /* Figure 16.6 */ }
28     public void pop( )
29       { /* Figure 16.6 */ }
30     public AnyType topAndPop( )
31       { /* Figure 16.7 */ }
32     public void push( AnyType x )
33       { /* Figure 16.5 */ }
34
35     private void doubleArray( )
36       { /* Implementation in online code  */ }
37
38     private AnyType [ ] theArray;
39     private int         topOfStack;
40
41     private static final int DEFAULT_CAPACITY = 10;
42 }
```

figure 16.2

Skeleton for the array-based stack class

figure 16.3

The zero-parameter constructor for the `ArrayStack` class

```
1       /**
2        * Construct the stack.
3        */
4       public ArrayStack( )
5       {
6           theArray = (AnyType []) new Object[ DEFAULT_CAPACITY ];
7           topOfStack = -1;
8       }
```

figure 16.4

The `isEmpty` and `makeEmpty` routines for the `ArrayStack` class

```
1       /**
2        * Test if the stack is logically empty.
3        * @return true if empty, false otherwise.
4        */
5       public boolean isEmpty( )
6       {
7           return topOfStack == -1;
8       }
9
10      /**
11       * Make the stack logically empty.
12       */
13      public void makeEmpty( )
14      {
15          topOfStack = -1;
16      }
```

figure 16.5

The push method for the ArrayStack class

```
1     /**
2      * Insert a new item into the stack.
3      * @param x the item to insert.
4      */
5     public void push( AnyType x )
6     {
7         if( topOfStack + 1 == theArray.length )
8             doubleArray( );
9         theArray[ ++topOfStack ] = x;
10    }
```

```
1       /**
2        * Get the most recently inserted item in the stack.
3        * Does not alter the stack.
4        * @return the most recently inserted item in the stack.
5        * @throws UnderflowException if the stack is empty.
6        */
7       public AnyType top( )
8       {
9           if( isEmpty( ) )
10              throw new UnderflowException( "ArrayStack top" );
11          return theArray[ topOfStack ];
12      }
13
14      /**
15       * Remove the most recently inserted item from the stack.
16       * @throws UnderflowException if the stack is empty.
17       */
18      public void pop( )
19      {
20          if( isEmpty( ) )
21              throw new UnderflowException( "ArrayStack pop" );
22          topOfStack--;
23      }
```

figure 16.6

The `top` and `pop` methods for the `ArrayStack` class

```
1       /**
2        * Return and remove the most recently inserted item
3        * from the stack.
4        * @return the most recently inserted item in the stack.
5        * @throws Underflow if the stack is empty.
6        */
7       public AnyType topAndPop( )
8       {
9           if( isEmpty( ) )
10              throw new UnderflowException( "ArrayStack topAndPop" );
11          return theArray[ topOfStack-- ];
12      }
```

figure 16.7

The `topAndPop` method for the `ArrayStack` class

Amortized running time

Array doubling is expensive in running time: $O(N)$.

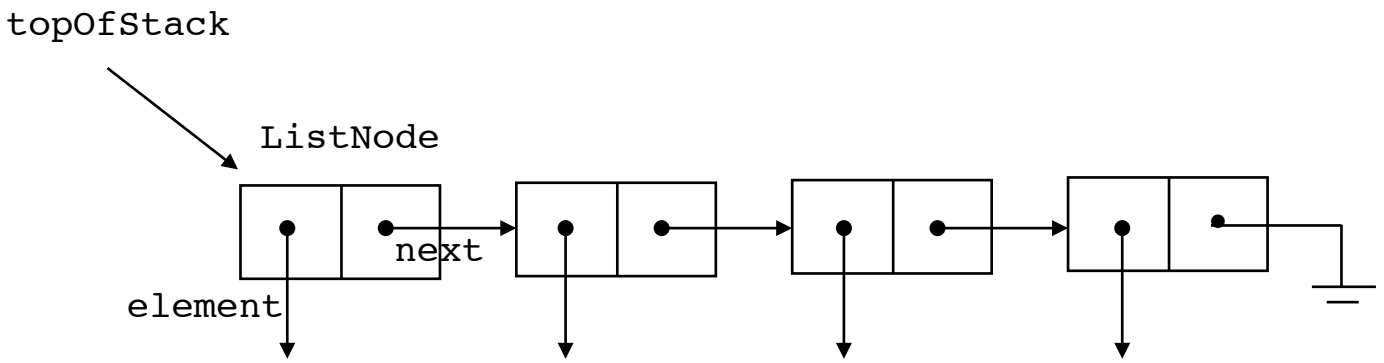
However, array doubling is infrequent because an array doubling that involves N elements must be preceded by at least $N/2$ pushes that do not involve an array doubling.

Consequently we can charge the $O(N)$ cost of the doubling over these $N/2$ easy pushes, thereby effectively raising the cost of each push by only a small constant.

In the "long run" `push` runs in $O(1)$ time.

Amortization: The paying off of debt in regular installments over a period of time.

Stack implemented with a linked list




```
class ListNode<AnyType> {
    ListNode(AnyType e, ListNode n) { element = e; next = n; }
    AnyType element;
    ListNode next;
}
```

```
1  package weiss.nonstandard;
2
3  // ListStack class
4  //
5  // CONSTRUCTION: with no initializer
6  //
7  // ******************PUBLIC OPERATIONS*********************
8  // void push( x )         --> Insert x
9  // void pop( )            --> Remove most recently inserted item
10 // AnyType top( )         --> Return most recently inserted item
11 // AnyType topAndPop( )   --> Return and remove most recent item
12 // boolean isEmpty( )     --> Return true if empty; else false
13 // void makeEmpty( )      --> Remove all items
14 // ******************ERRORS********************************
15 // top, pop, or topAndPop on empty stack
16
17 public class ListStack<AnyType> implements Stack<AnyType>
18 {
19     public boolean isEmpty( )
20       { return topOfStack == null; }
21     public void makeEmpty( )
22       { topOfStack = null; }
23
24     public void push( AnyType x )
25       { /* Figure 16.20 */ }
26     public void pop( )
27       { /* Figure 16.20 */ }
28     public AnyType top( )
29       { /* Figure 16.21 */ }
30     public AnyType topAndPop( )
31       { /* Figure 16.21 */ }
32
33     private ListNode<AnyType> topOfStack = null;
34 }
35
36 // Basic node stored in a linked list.
37 // Note that this class is not accessible outside
38 // of package weiss.nonstandard
39 class ListNode<AnyType>
40 {
41     public ListNode( AnyType theElement )
42       { this( theElement, null ); }
43
44     public ListNode( AnyType theElement, ListNode<AnyType> n )
45       { element = theElement; next = n; }
46
47     public AnyType   element;
48     public ListNode next;
49 }
```

figure 16.19

Skeleton for linked list-based stack class

figure 16.20

The push and pop routines for the ListStack class

```
1       /**
2        * Insert a new item into the stack.
3        * @param x the item to insert.
4        */
5       public void push( AnyType x )
6       {
7           topOfStack = new ListNode<AnyType>( x, topOfStack );
8       }
9
10      /**
11       * Remove the most recently inserted item from the stack.
12       * @throws UnderflowException if the stack is empty.
13       */
14      public void pop( )
15      {
16          if( isEmpty( ) )
17              throw new UnderflowException( "ListStack pop" );
18          topOfStack = topOfStack.next;
19      }
```

```
1       /**
2        * Get the most recently inserted item in the stack.
3        * Does not alter the stack.
4        * @return the most recently inserted item in the stack.
5        * @throws UnderflowException if the stack is empty.
6        */
7       public AnyType top( )
8       {
9           if( isEmpty( ) )
10              throw new UnderflowException( "ListStack top" );
11          return topOfStack.element;
12      }
13
14      /**
15       * Return and remove the most recently inserted item
16       * from the stack.
17       * @return the most recently inserted item in the stack.
18       * @throws UnderflowException if the stack is empty.
19       */
20      public AnyType topAndPop( )
21      {
22          if( isEmpty( ) )
23              throw new UnderflowException( "ListStack topAndPop" );
24
25          AnyType topItem = topOfStack.element;
26          topOfStack = topOfStack.next;
27          return topItem;
28      }
```

figure 16.21

The `top` and `topAndPop` routines for the `ListStack` class

figure 16.28

A simplified Collections-style `Stack` class, based on the `ArrayList` class

```
1  package weiss.util;
2
3  /**
4   * Stack class. Unlike java.util.Stack, this is not extended from
5   * Vector. This is the minimum respectable set of operations.
6   */
7  public class Stack<AnyType> implements java.io.Serializable
8  {
9      public Stack( )
10     {
11         items = new ArrayList<AnyType>( );
12     }
13
14     public AnyType push( AnyType x )
15     {
16         items.add( x );                                    O(1) amortized time
17         return x;
18     }
19
20     public AnyType pop( )
21     {
22         if( isEmpty( ) )
23             throw new EmptyStackException( );
24         return items.remove( items.size( ) - 1 );          O(1) time
25     }
26
27     public AnyType peek( )
28     {
29         if( isEmpty( ) )
30             throw new EmptyStackException( );
31         return items.get( items.size( ) - 1 );
32     }
33
34     public boolean isEmpty( )
35     {
36         return size( ) == 0;
37     }
38
39     public int size( )
40     {
41         return items.size( );
42     }
43
44     public void clear( )
45     {
46         items.clear( );
47     }
48
49     private ArrayList<AnyType> items;
50 }
```

top

Class `Stack` in `java.util`

Method Summary	
boolean	**empty**() Tests if this stack is empty.
Object	**peek**() Looks at the object at the top of this stack without removing it from the stack.
Object	**pop**() Removes the object at the top of this stack and returns that object as the value of this function.
Object	**push**(Object item) Pushes an item onto the top of this stack.
int	**search**(Object o) Returns the 1-based position where an object is on this stack.

A more complete and consistent set of LIFO stack operations is provided by the Deque (double-ended queue) interface and its implementations, which should be used in preference to this class. For example ArrayDeque and LinkedList.

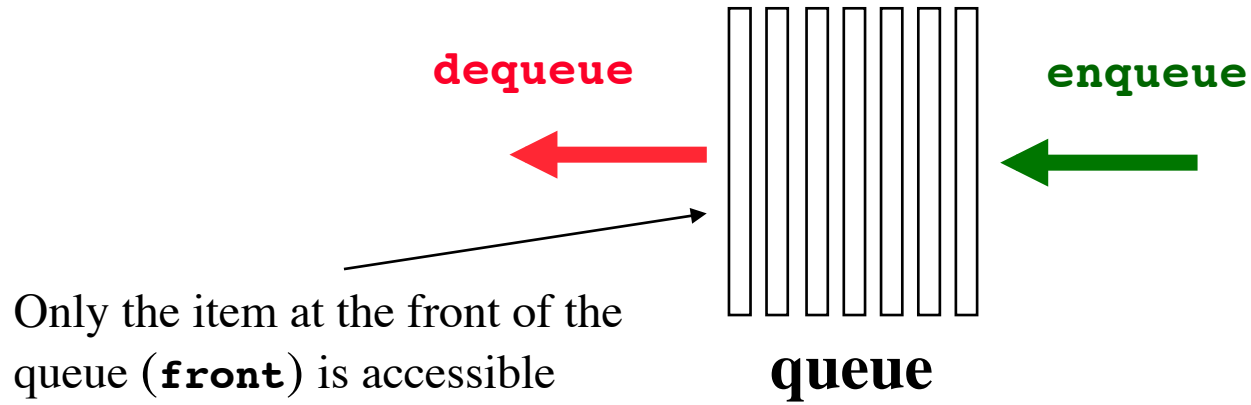
Queue

(**FIFO** = **F**irst**I**n**F**irst**O**ut)

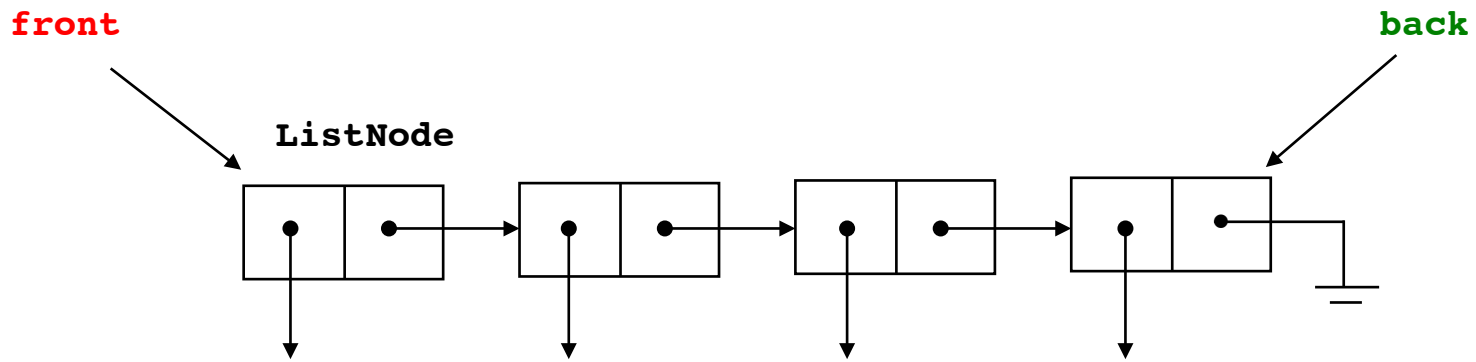
A **queue** is a sequence of items of the same type that provides the following two operations:

`enqueue(x):` Insert the item **`x`** at the back of the queue

`dequeue:` Remove the item at the front of the queue



Queue implemented with a linked list




```
class ListNode<AnyType) {
    ListNode(AnyType e) { element = e; }
    AnyType element;
    ListNode next;
}
```

figure 16.23

Skeleton for the linked list-based queue class

```
1  package weiss.nonstandard;
2
3  // ListQueue class
4  //
5  // CONSTRUCTION: with no initializer
6  //
7  // ******************PUBLIC OPERATIONS*********************
8  // void enqueue( x )      --> Insert x
9  // AnyType getFront( )    --> Return least recently inserted item
10 // AnyType dequeue( )     --> Return and remove least recent item
11 // boolean isEmpty( )     --> Return true if empty; else false
12 // void makeEmpty( )      --> Remove all items
13 // ******************ERRORS********************************
14 // getFront or dequeue on empty queue
15
16 public class ListQueue<AnyType>
17 {
18     public ListQueue( )
19       { /* Figure 16.24 */ }
20     public boolean isEmpty( )
21       { /* Figure 16.27 */ }
22     public void enqueue( AnyType x )
23       { /* Figure 16.25 */ }
24     public AnyType dequeue( )
25       { /* Figure 16.25 */ }
26     public AnyType getFront( )
27       { /* Figure 16.27 */ }
28     public void makeEmpty( )
29       { /* Figure 16.27 */ }
30
31     private ListNode<AnyType> front;
32     private ListNode<AnyType> back;
33 }
```

figure 16.24

Constructor for the linked list-based `ListQueue` class

```
1       /**
2        * Construct the queue.
3        */
4       public ListQueue( )
5       {
6           front = back = null;
7       }
```

```
1     /**
2      * Insert a new item into the queue.
3      * @param x the item to insert.
4      */
5     public void enqueue( AnyType x )
6     {
7         if( isEmpty( ) )    // Make a queue of one element
8             back = front = new ListNode<AnyType>( x );
9         else                // Regular case
10            back = back.next = new ListNode<AnyType>( x );
11    }
12
13    /**
14     * Return and remove the least recently inserted item
15     * from the queue.
16     * @return the least recently inserted item in the queue.
17     * @throws UnderflowException if the queue is empty.
18     */
19    public AnyType dequeue( )
20    {
21        if( isEmpty( ) )
22            throw new UnderflowException( "ListQueue dequeue" );
23
24        AnyType returnValue = front.element;
25        front = front.next;
26        return returnValue;
27    }
```

Note the execution order (right-to-left)

O(1) time

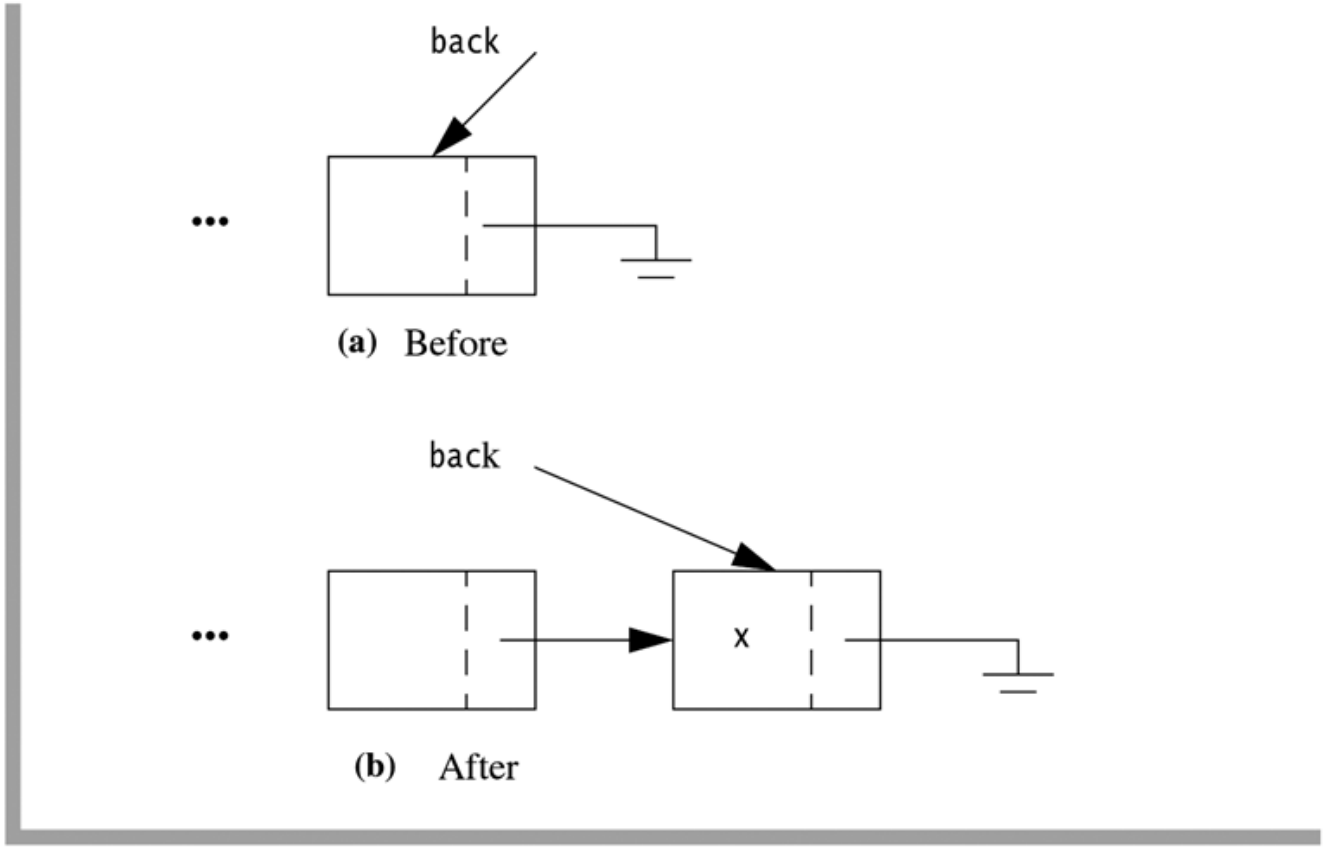
O(1) time

figure 16.25

The `enqueue` and `dequeue` routines for the `ListQueue` class

figure 16.26

The enqueue operation for the linked list-based implementation



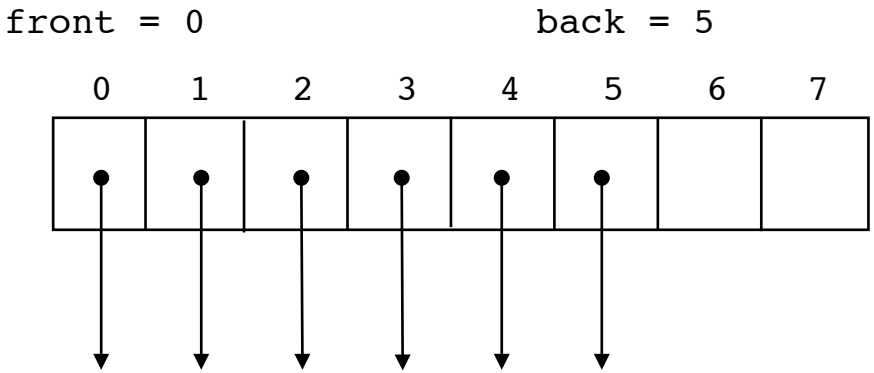

```
back = back.next = new ListNode<AnyType>( x );
```

figure 16.27

Supporting routines for the `ListQueue` class

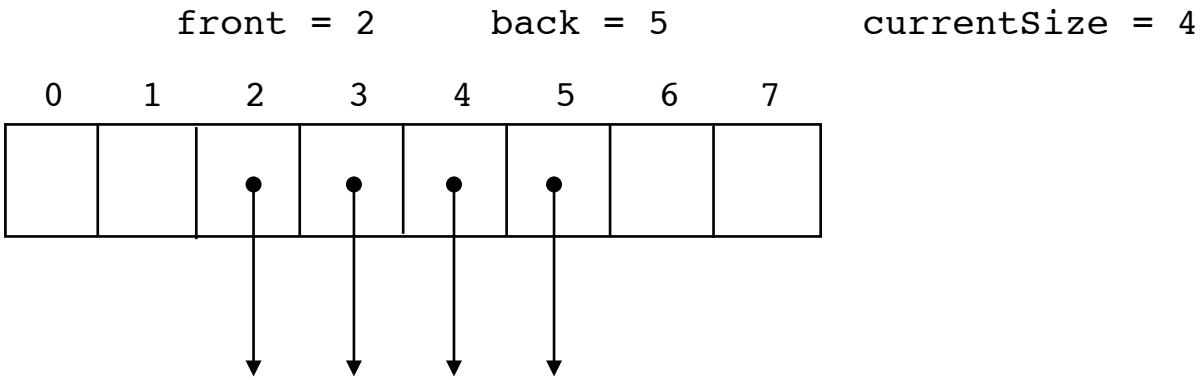
```
1       /**
2        * Get the least recently inserted item in the queue.
3        * Does not alter the queue.
4        * @return the least recently inserted item in the queue.
5        * @throws UnderflowException if the queue is empty.
6        */
7       public AnyType getFront( )
8       {
9           if( isEmpty( ) )
10              throw new UnderflowException( "ListQueue getFront" );
11          return front.element;
12      }
13
14      /**
15       * Make the queue logically empty.
16       */
17      public void makeEmpty( )
18      {
19          front = null;
20          back = null;
21      }
22
23      /**
24       * Test if the queue is logically empty.
25       */
26      public boolean isEmpty( )
27      {
28          return front == null;
29      }
```

Queue implemented with an array

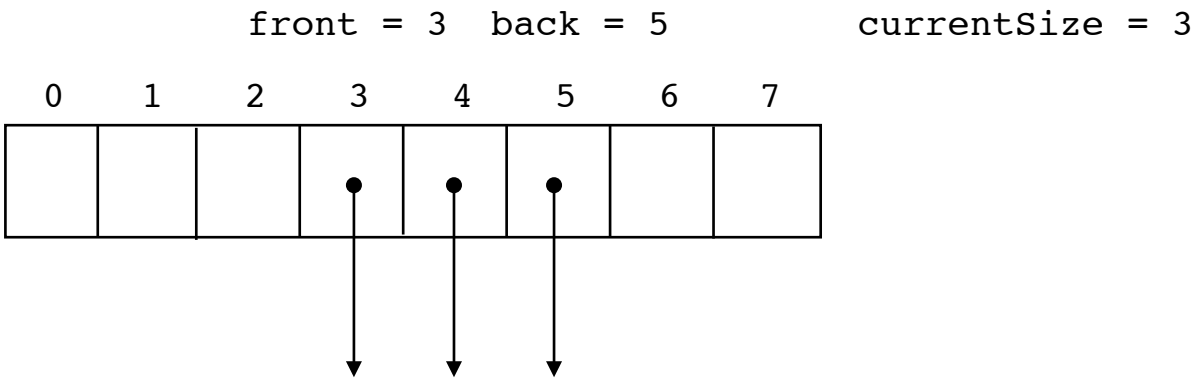


We must avoid shifting the items when an dequeue operation is executed.

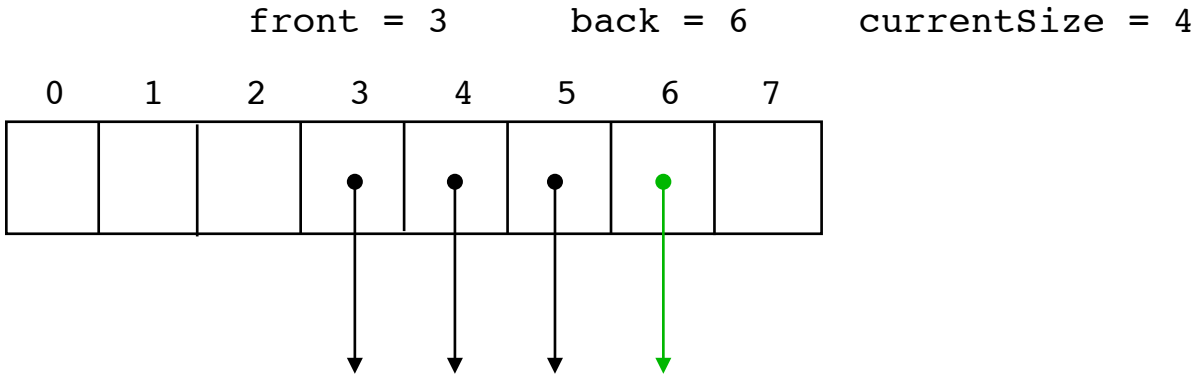
Circular array



dequeue:



enqueue:



enqueue with *wraparound*

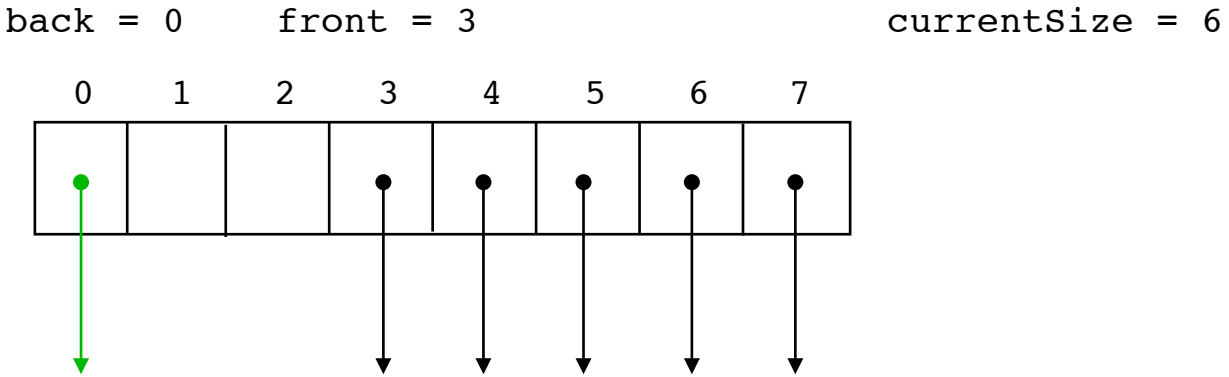
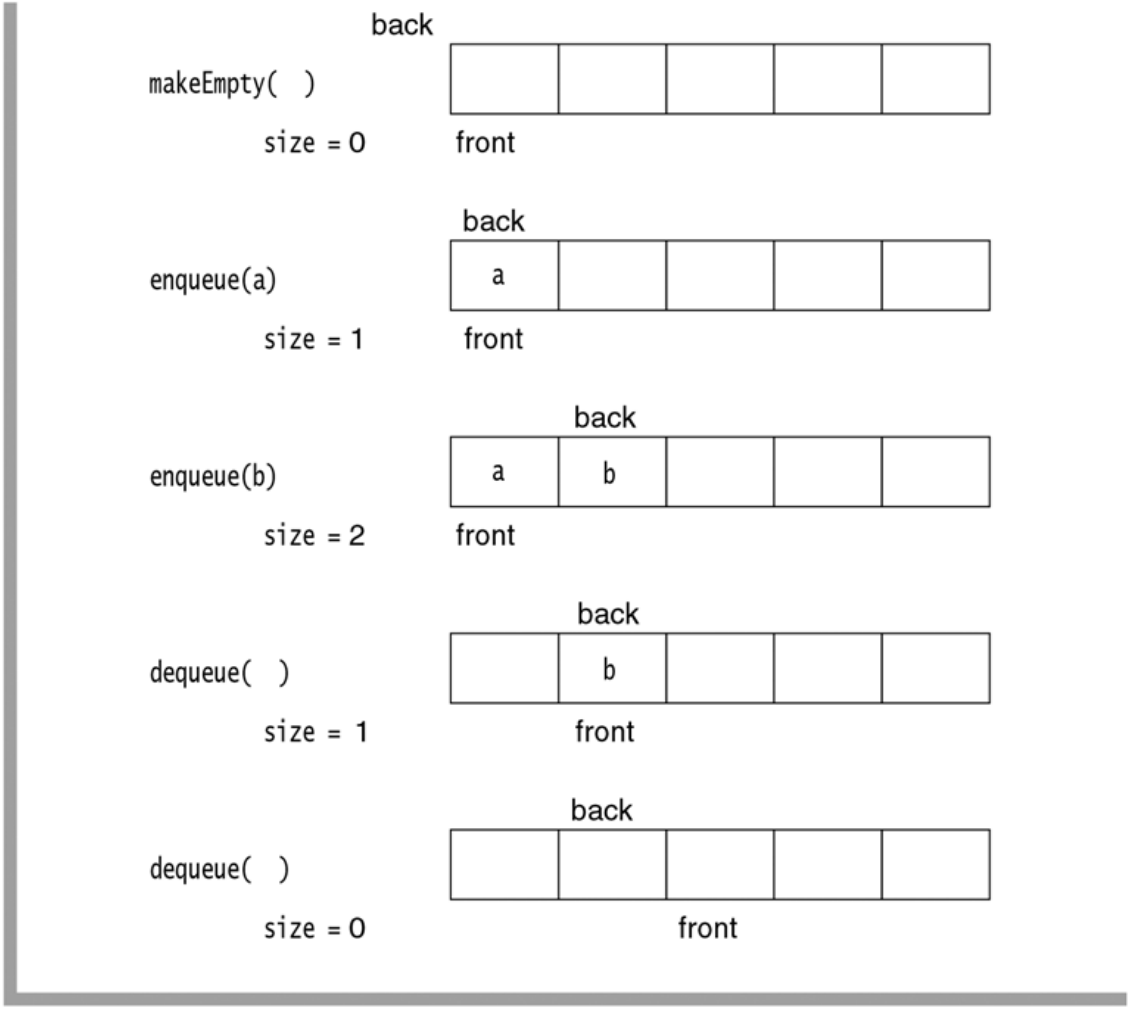


figure 16.8

Basic array implementation of the queue



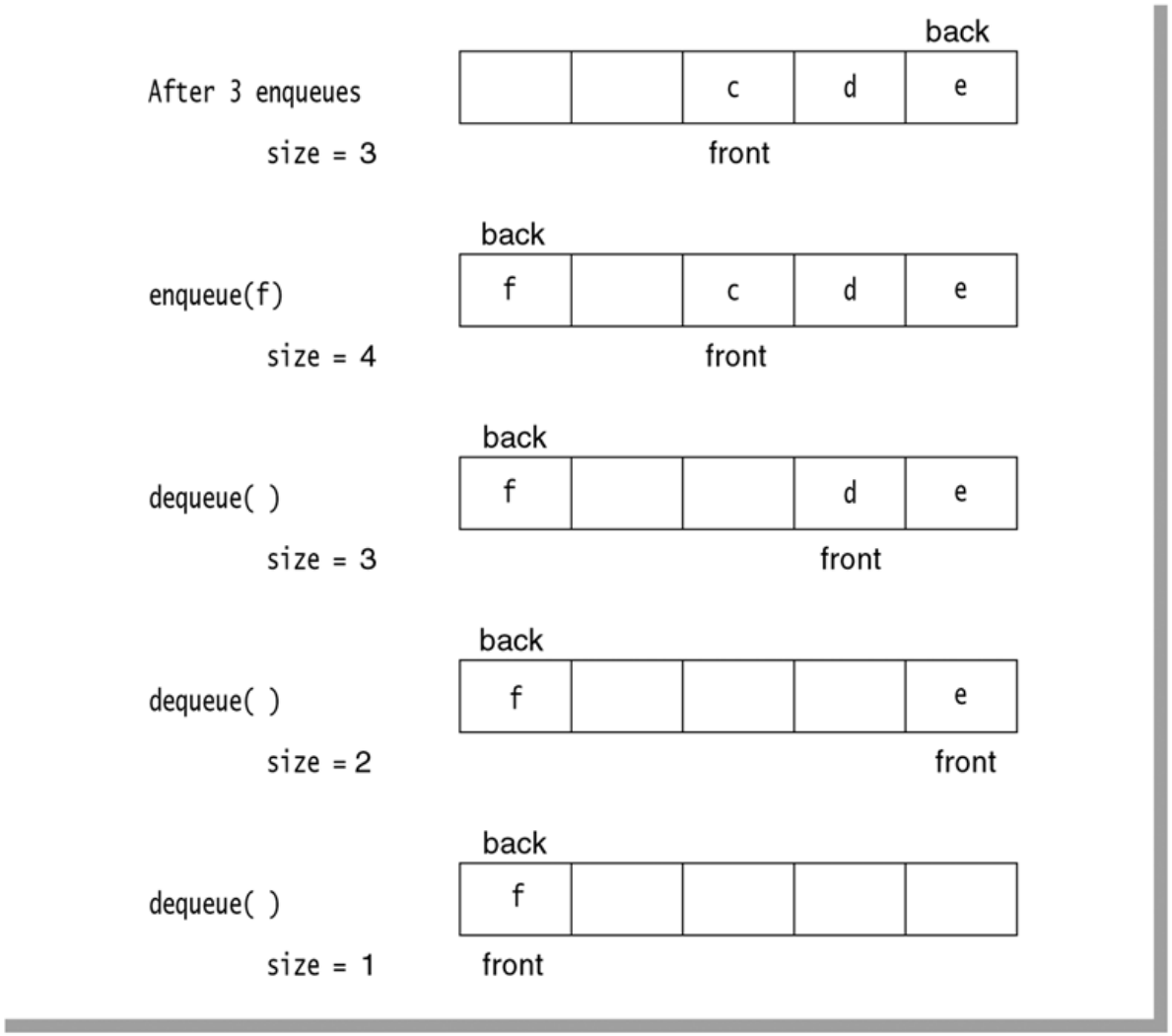


figure 16.9

Array implementation of the queue with wraparound

figure 16.10

Skeleton for the array-based queue class

```
1  package weiss.nonstandard;
2
3  // ArrayQueue class
4  //
5  // CONSTRUCTION: with no initializer
6  //
7  // ******************PUBLIC OPERATIONS*********************
8  // void enqueue( x )      --> Insert x
9  // AnyType getFront( )    --> Return least recently inserted item
10 // AnyType dequeue( )     --> Return and remove least recent item
11 // boolean isEmpty( )     --> Return true if empty; else false
12 // void makeEmpty( )      --> Remove all items
13 // ******************ERRORS********************************
14 // getFront or dequeue on empty queue
15
16 public class ArrayQueue<AnyType>
17 {
18     public ArrayQueue( )
19       { /* Figure 16.12 */ }
20
21     public boolean isEmpty( )
22       { /* Figure 16.13 */ }
23     public void makeEmpty( )
24       { /* Figure 16.17 */ }
25     public AnyType dequeue( )
26       { /* Figure 16.16 */ }
27     public AnyType getFront( )
28       { /* Figure 16.16 */ }
29     public void enqueue( AnyType x )
30       { /* Figure 16.14 */ }
31
32     private int increment( int x )
33       { /* Figure 16.11 */ }
34     private void doubleQueue( )
35       { /* Figure 16.15 */ }
36
37     private AnyType [ ] theArray;
38     private int         currentSize;
39     private int         front;
40     private int         back;
41
42     private static final int DEFAULT_CAPACITY = 10;
43 }
```

```
1       /**
2        * Internal method to increment with wraparound.
3        * @param x any index in theArray's range.
4        * @return x+1, or 0 if x is at the end of theArray.
5        */
6       private int increment( int x )
7       {
8           if( ++x == theArray.length )
9               x = 0;
10          return x;
11      }
```

figure 16.11

The wraparound routine

```
1       /**
2        * Construct the queue.
3        */
4       public ArrayQueue( )
5       {
6           theArray = (AnyType []) new Object[ DEFAULT_CAPACITY ];
7           makeEmpty( );
8       }
```

figure 16.12

The constructor for the `ArrayQueue` class

```
1       /**
2        * Test if the queue is logically empty.
3        * @return true if empty, false otherwise.
4        */
5       public boolean isEmpty( )
6       {
7           return currentSize == 0;
8       }
```

figure 16.13

The `isEmpty` routine for the `ArrayQueue` class

figure 16.14

The `enqueue` routine for the `ArrayQueue` class

```
1       /**
2        * Insert a new item into the queue.
3        * @param x the item to insert.
4        */
5       public void enqueue( AnyType x )
6       {
7           if( currentSize == theArray.length )
8               doubleQueue( );
9           back = increment( back );
10          theArray[ back ] = x;
11          currentSize++;
12      }
```

$O(1)$ amortized time

```
1       /**
2        * Internal method to expand theArray.
3        */
4       private void doubleQueue( )
5       {
6           AnyType [ ] newArray;
7
8           newArray = (AnyType []) new Object[ theArray.length * 2 ];
9
10              // Copy elements that are logically in the queue
11          for( int i = 0; i < currentSize; i++, front = increment( front ) )
12              newArray[ i ] = theArray[ front ];
13
14          theArray = newArray;
15          front = 0;
16          back = currentSize - 1;
17      }
```

figure 16.15

Dynamic expansion for the `ArrayQueue` class

```
1       /**
2        * Return and remove the least recently inserted item
3        * from the queue.
4        * @return the least recently inserted item in the queue.
5        * @throws UnderflowException if the queue is empty.
6        */
7       public AnyType dequeue( )
8       {
9           if( isEmpty( ) )
10              throw new UnderflowException( "ArrayQueue dequeue" );
11          currentSize--;
12
13          AnyType returnValue = theArray[ front ];
14          front = increment( front );
15          return returnValue;
16      }
17
18      /**
19       * Get the least recently inserted item in the queue.
20       * Does not alter the queue.
21       * @return the least recently inserted item in the queue.
22       * @throws UnderflowException if the queue is empty.
23       */
24      public AnyType getFront( )
25      {
26          if( isEmpty( ) )
27              throw new UnderflowException( "ArrayQueue getFront" );
28          return theArray[ front ];
29      }
```

figure 16.16

The `dequeue` and `getFront` routines for the `ArrayQueue` class

O(1) time

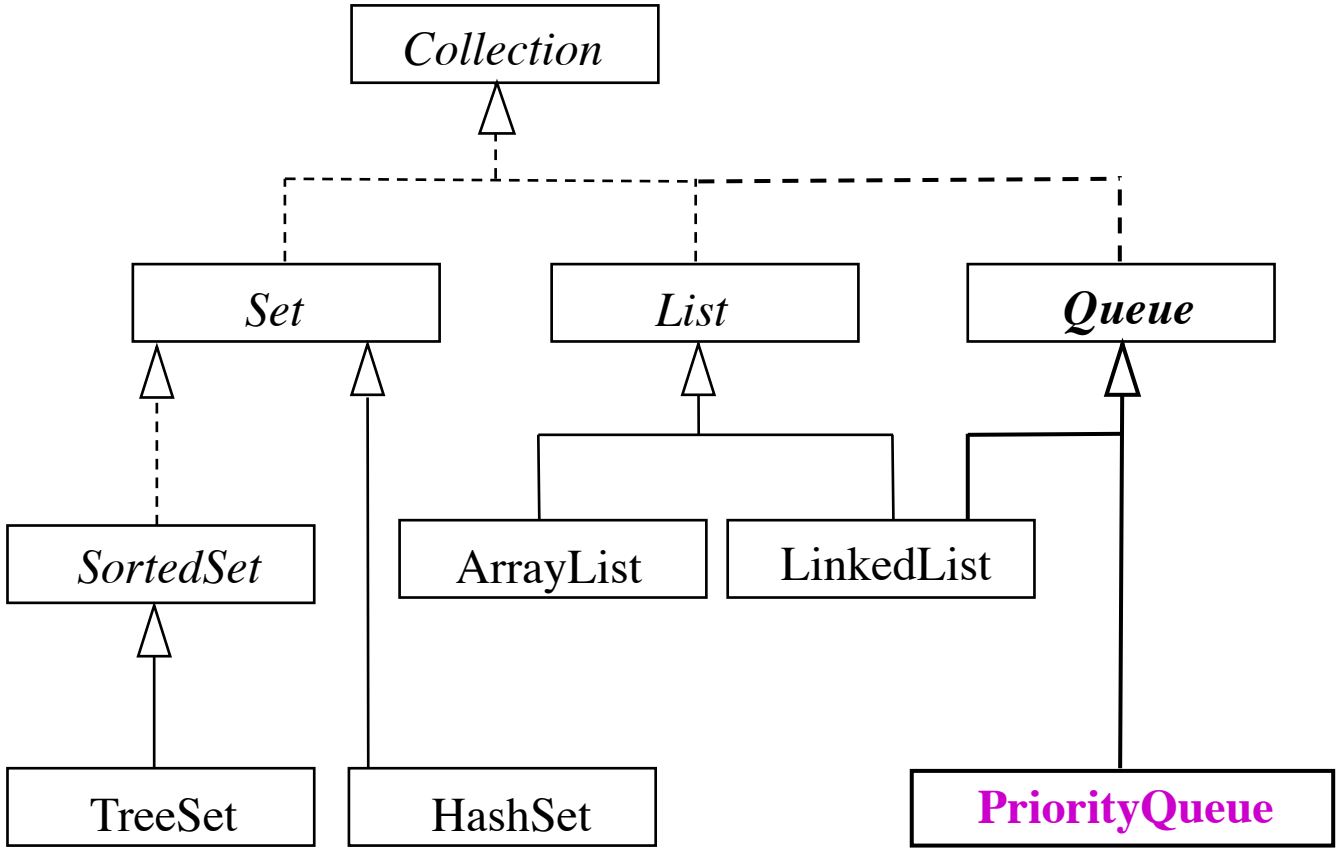
O(1) time

```
1       /**
2        * Make the queue logically empty.
3        */
4       public void makeEmpty( )
5       {
6           currentSize = 0;
7           front = 0;
8           back = -1;
9       }
```

figure 16.17

The `makeEmpty` routine for the `ArrayQueue` class

New collections in Java 5

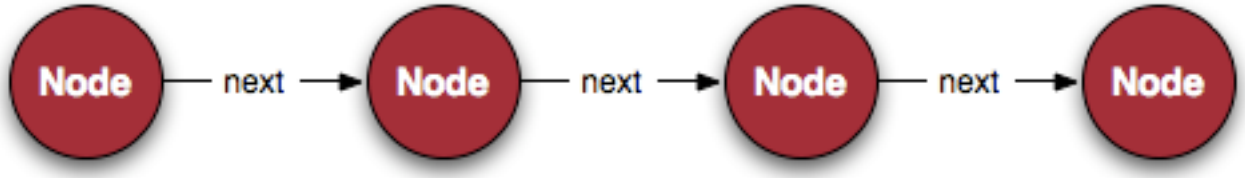


Interface `Queue` in `java.util`

Method Summary	
E	**`element`**`()` Retrieves, but does not remove, the head of this queue.
boolean	**`offer`**`(E o)` Inserts the specified element into this queue, if possible.
E	**`peek`**`()` Retrieves, but does not remove, the head of this queue, returning `null` if this queue is empty.
E	**`poll`**`()` Retrieves and removes the head of this queue, or `null` if this queue is empty.
E	**`remove`**`()` Retrieves and removes the head of this queue.

Some implementing classes: `LinkedList`, `PriorityQueue`

Linked lists



Disadvantages of storing a sequence of items as an array

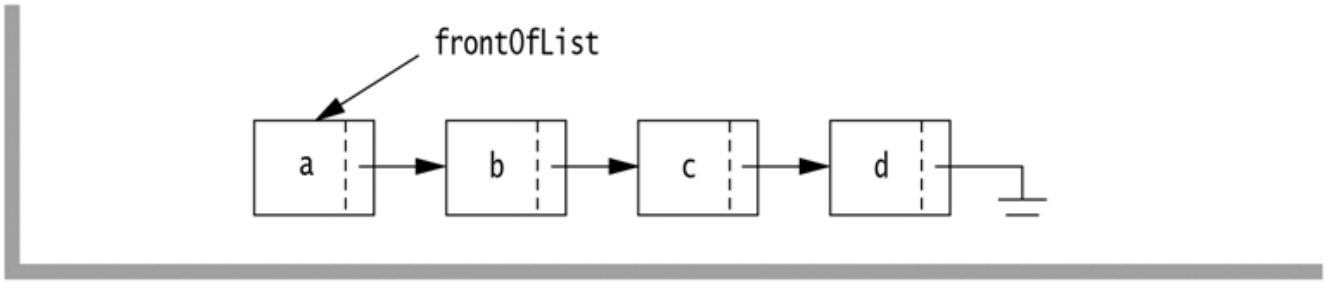
(1) Insertion and removal of items take time proportional to the length of the array

(2) Arrays have a fixed length

Singly linked list

figure 17.1

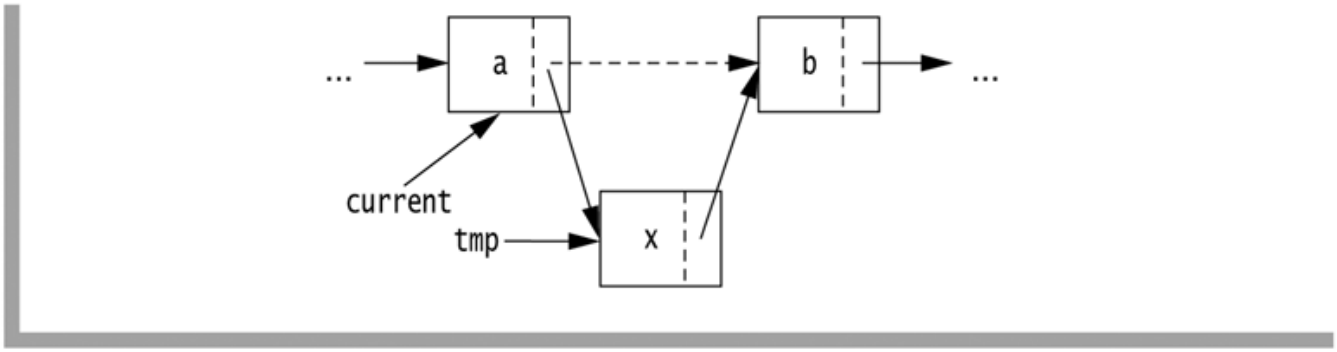
Basic linked list



Insertion

figure 17.2

Insertion in a linked list: Create new node (`tmp`), copy in `x`, set `tmp`'s next link, and set `current`'s next link.




```
tmp = new Node(x);
tmp.next = current.next;
current.next = tmp;
```

Deletion

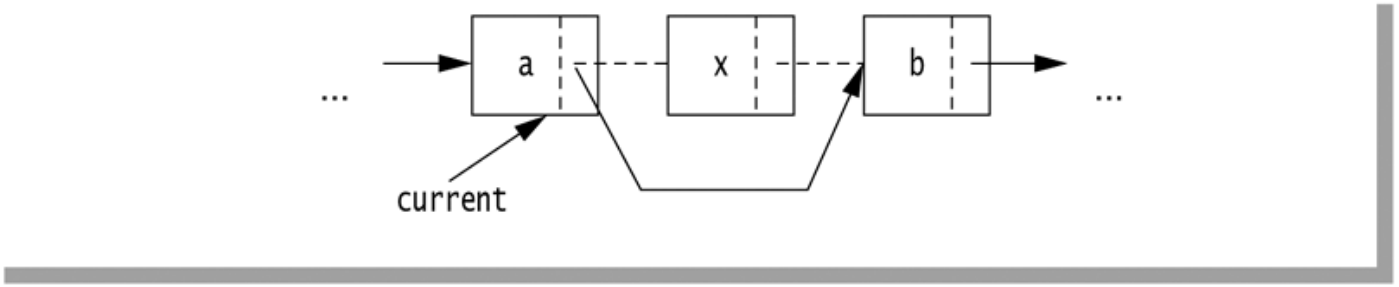


figure 17.3

Deletion from a linked list

```
current.next = current.next.next;
```

Using a header node for easy removal of the first element

figure 17.4

Using a header node for the linked list

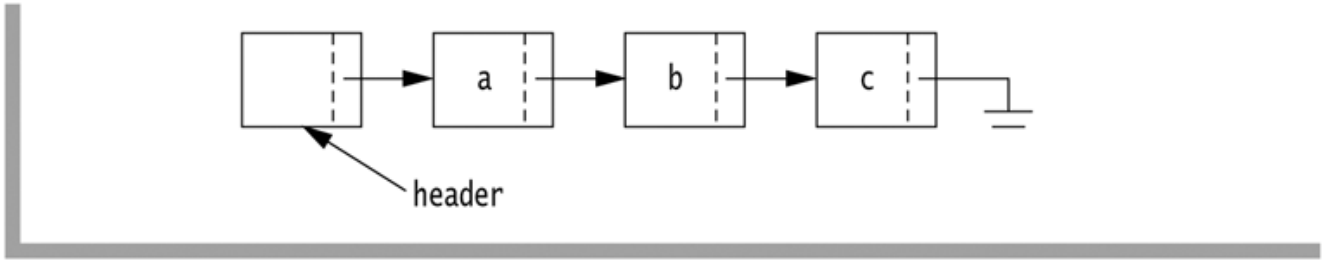
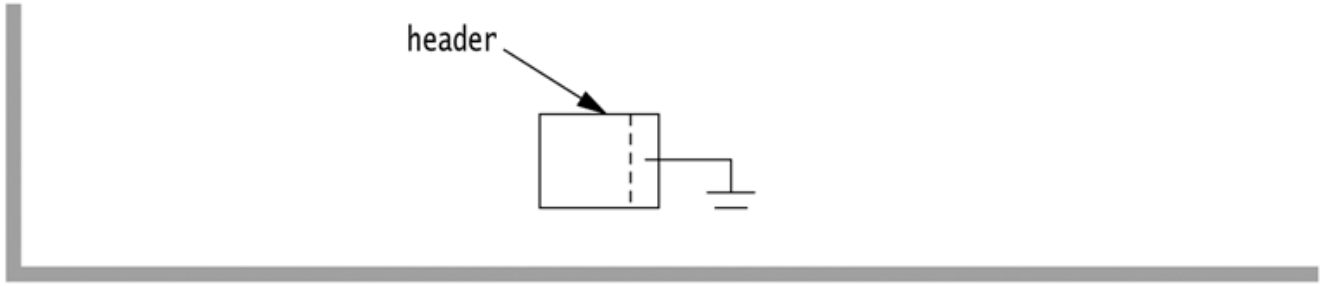


figure 17.5

Empty list when a header node is used



Doubly linked list

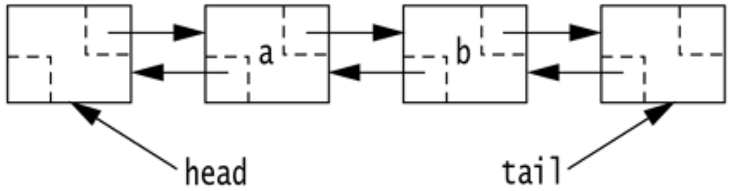


figure 17.15

A doubly linked list

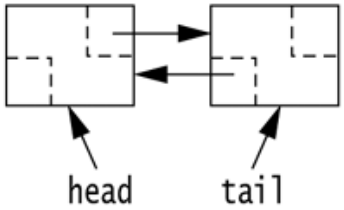


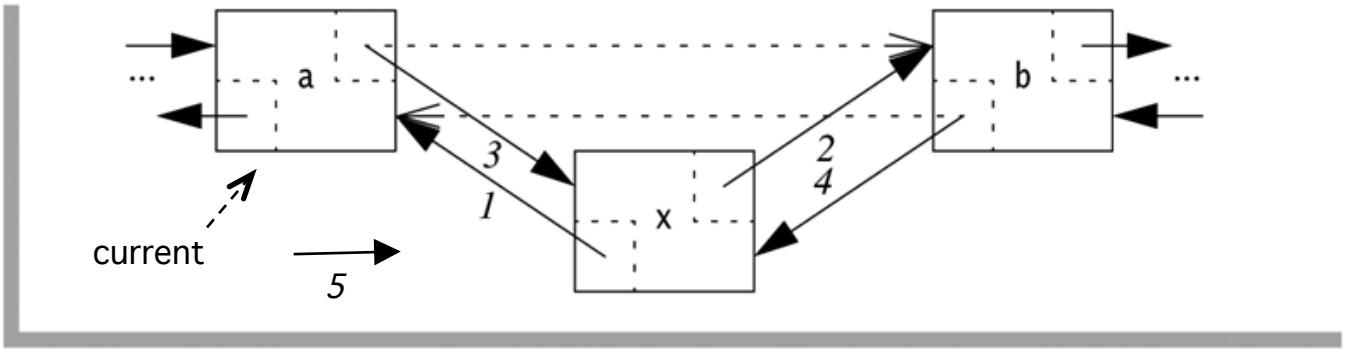
figure 17.16

An empty doubly linked list

Insertion

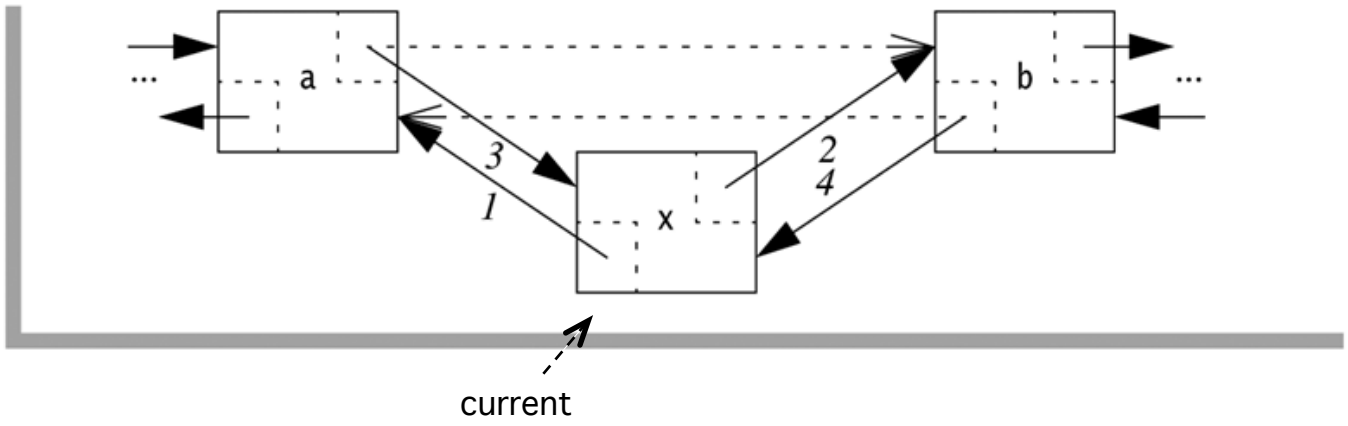
figure 17.17

Insertion in a doubly linked list by getting new node and then changing pointers in the order indicated




```
newNode = new DoublyLinkedListNode(x);
newNode.prev = current;                    // 1
newNode.next = current.next;               // 2
current.next = newNode;                    // 3
newNode.next.prev = newNode;               // 4
current = newNode;                         // 5
```

Deletion




```
current.prev.next = current.next;   // set a's next link
current.next.prev = current.prev;   // set b's prev link
current.next = current.prev = null;
current = head;                     // So current is not stale
```

Circularly linked list

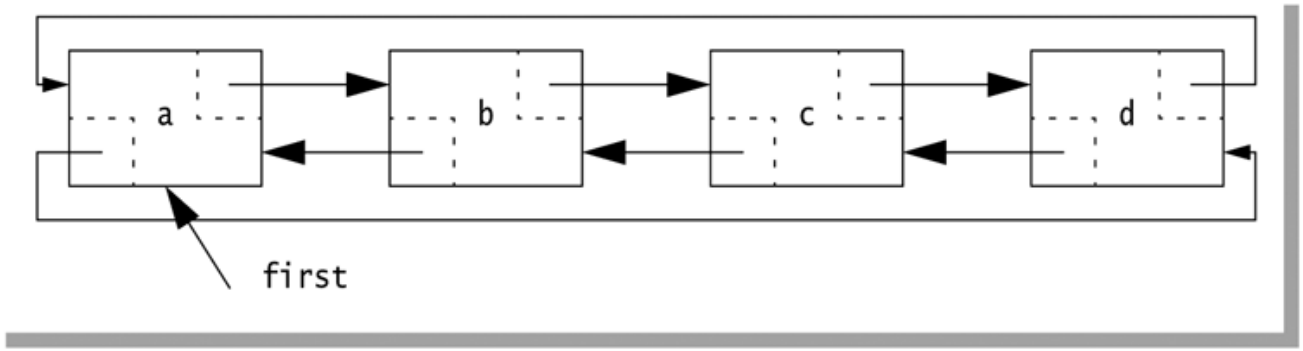


figure 17.18

A circularly and doubly linked list