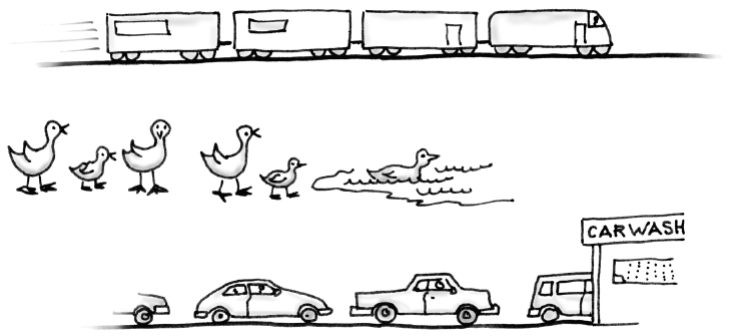
CSC 273 – Data Structures

Lecture 7 - Queues, Deques, and Priority Queues

The ADT Queue

- A queue is another name for a waiting line
- Used within operating systems and to simulate real-world events
  - Come into play whenever processes or events must wait
- Entries organized first-in, first-out

The ADT Queue



Some everyday queues

The ADT Queue

- Terminology
  - Item added first, or earliest, is at the front of the queue
  - Item added most recently is at the back of the queue
- Additions to a software queue must occur at its back
- Client can look at or remove only the entry at the front of the queue

The ADT Queue

Abstract Data Type: Queue

Data

- A collection of objects in chronological order and having the same data type

Operations

Pseudocode	UML	Description
`enqueue(newEntry)`	`+enqueue(newEntry: integer): void`	Task: Adds a new entry to the back of the queue. Input: `newEntry` is the new entry. Output: None.
`dequeue()`	`+dequeue(): T`	Task: Removes and returns the entry at the front of the queue. Input: None. Output: Returns the queue's front entry. Throws an exception if the queue is empty before the operation.

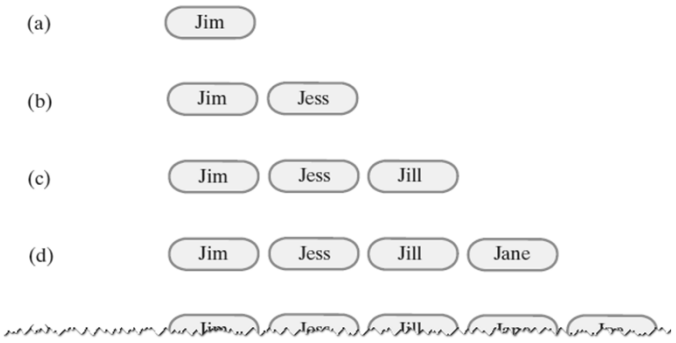
The ADT Queue

`getFront()`	`+getFront(): T`	Task: Retrieves the queue's front entry without changing the queue in any way. Input: None. Output: Returns the queue's front entry. Throws an exception if the queue is empty.
`isEmpty()`	`+isEmpty(): boolean`	Task: Detects whether the queue is empty. Input: None. Output: Returns true if the queue is empty.
`clear()`	`+clear(): void`	Task: Removes all entries from the queue. Input: None. Output: None.

The ADT Queue

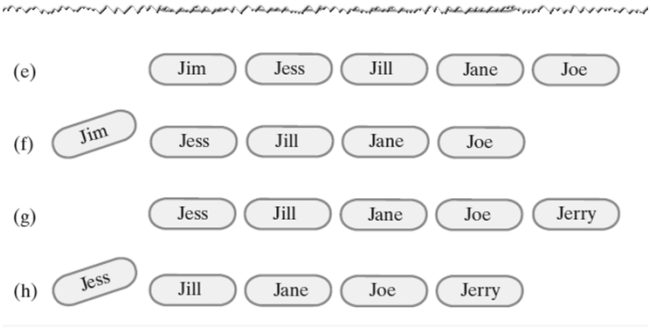
```java
public interface QueueInterface<T>
{
   /** Adds a new entry to the back of this queue.
       @param newEntry  An object to be added. */
   public void enqueue(T newEntry);

   /** Removes and returns the entry at the front of this queue.
       @return  The object at the front of the queue.
       @throws  EmptyQueueException if the queue is empty before the operation.
   public T dequeue();

   /** Retrieves the entry at the front of this queue.
       @return  The object at the front of the queue.
       @throws  EmptyQueueException if the queue is empty. */
   public T getFront();

   /** Detects whether this queue is empty.
       @return  True if the queue is empty, or false otherwise. */
   public boolean isEmpty();

   /** Removes all entries from this queue. */
   public void clear();
} // end QueueInterface
```

The ADT Queue



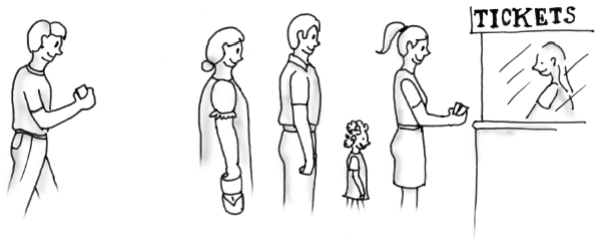
A queue of strings after (a) enqueue adds *Jim*; (b) enqueue adds *Jess*; (c) enqueue adds *Jill*; (d) enqueue adds *Jane*;

TheADT Queue



A queue of strings after (e) enqueue adds *Joe*;
(f) dequeue retrieves and removes *Jim*;
(g) enqueue adds *Jerry*;
(h) dequeue retrieves and removes *Jess*

Simulating a Waiting Line



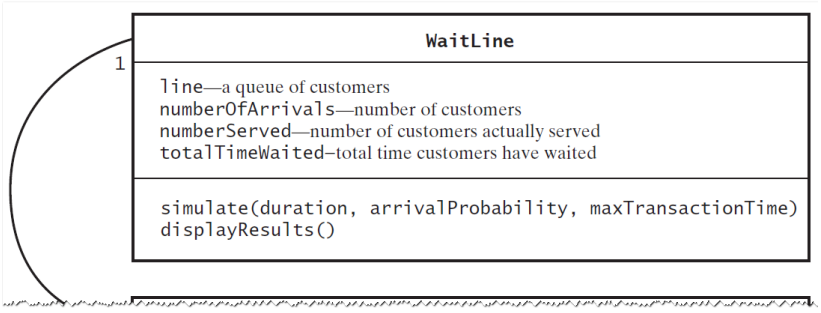
A line, or queue, of people

Simulating a Waiting Line

WaitLine
Responsibilities
Simulate customers entering and leaving a waiting line
Display number served, total wait time, average wait time, and number left in line
Collaborations
Customer

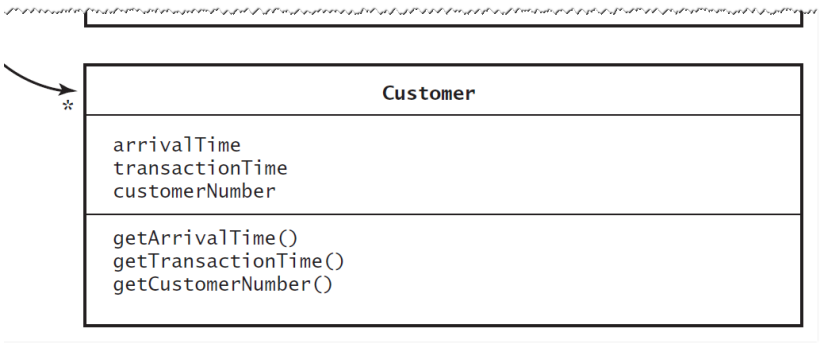
A CRC card for the class **`WaitLine`**

Simulating a Waiting Line



A diagram of the classes **`WaitLine`** *and* **`Customer`**

Simulating a Waiting Line



A diagram of the classes **`WaitLine`** *and* **`Customer`**

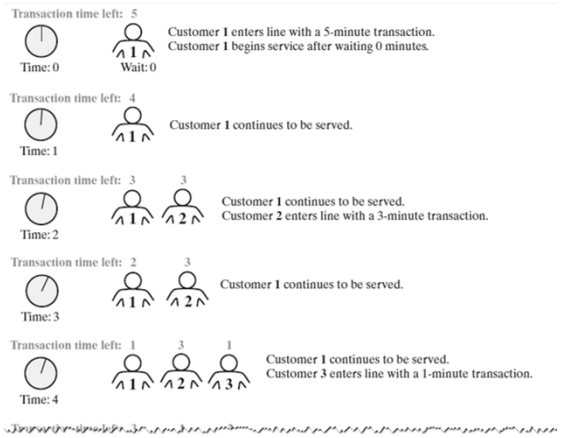
Simulating a Waiting Line

Algorithm `simulate(duration, arrivalProbability, maxTransactionTime)`

```
transactionTimeLeft = 0
for (clock = 0; clock < duration; clock++)
{
   if (a new customer arrives)
   {
      numberOfArrivals++
      transactionTime = a random time that does not exceed maxTransactionTime
      nextArrival = a new customer containing clock, transactionTime, and
                    a customer number that is numberOfArrivals
      line.enqueue(nextArrival)
   }
   if (transactionTimeLeft > 0) // If present customer is still being served
      transactionTimeLeft--
   else if (!line.isEmpty())
   {
      nextCustomer = line.dequeue()
      transactionTimeLeft = nextCustomer.getTransactionTime() - 1
      timeWaited = clock - nextCustomer.getArrivalTime()
      totalTimeWaited = totalTimeWaited + timeWaited
      numberServed++
   }
}
```

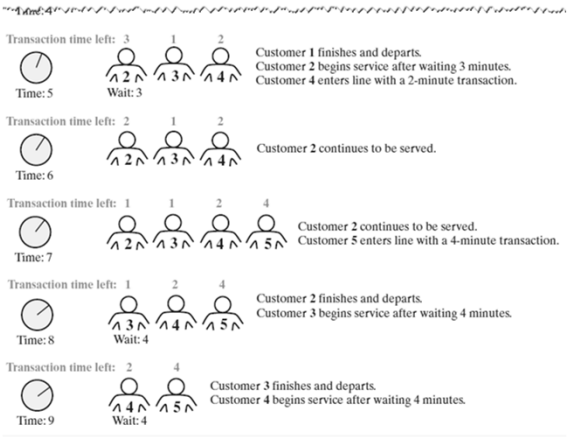
Algorithm for **`simulate`**

Simulating a Waiting Line



A simulated waiting line

Simulating a Waiting Line



A simulated waiting line

WaitLine.java

```
public class WaitLine {
  private QueueInterface<Customer> line;
  private int numberOfArrivals;
  private int numberServed;
  private int totalTimeWaited;

  public WaitLine()    {
    line = new LinkedQueue<>();
    reset();
  }
```

```
  // Simulates a waiting line with one serving
  // agent.
  //    duration - The number of simulated
  //               minutes
  //    arrivalProbability -
  //             A real number between 0 and 1,
  //             and the probability that a
  //             customer arrives at a given time
  //    maxTransactionTime -
  //             The longest transaction time for
  //             a customer
  public void simulate(int duration,
              double arrivalProbability,
              int maxTransactionTime)      {
    int transactionTimeLeft = 0;
```

```
    for (int clock = 0; clock < duration;
                                clock++)       {
      if (Math.random() < arrivalProbability)  {
        numberOfArrivals++;
        int transactionTime = (int)(Math.random()
                      * maxTransactionTime + 1);
        Customer nextArrival
            = new Customer(clock,
             transactionTime, numberOfArrivals);
        line.enqueue(nextArrival);
        System.out.println("Customer "
               + numberOfArrivals
               + " enters line at time " + clock
               + ". Transaction time is "
               + transactionTime);
      }
```

```
      if (transactionTimeLeft > 0)
        transactionTimeLeft--;
      else if (!line.isEmpty())          {
        Customer nextCustomer = line.dequeue();
        transactionTimeLeft =
           nextCustomer.getTransactionTime() - 1;
        int timeWaited
         = clock - nextCustomer.getArrivalTime();
        totalTimeWaited
                = totalTimeWaited + timeWaited;
        numberServed++;
        System.out.println("Customer "
             + nextCustomer.getCustomerNumber()
             + " begins service at time " + clock
             + ". Time waited is " + timeWaited);
         }
      }
    }
```

```
  // Displays summary results of the simulation
  public void displayResults()    {
    System.out.println();
    System.out.println("Number served = "
                              + numberServed);
    System.out.println("Total time waited = "
                     + totalTimeWaited);
    double averageTimeWaited =
        ((double)totalTimeWaited) / numberServed;
    System.out.println("Average time waited = "
                      + averageTimeWaited);
    int leftInLine
          = numberOfArrivals - numberServed;
    System.out.println("Number left in line = "
                                   + leftInLine);
  }
```

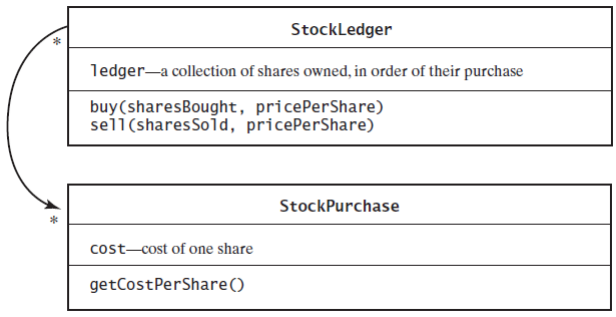
```
   // Initializes the simulation
   public final void reset()  {
      line.clear();
      numberOfArrivals = 0;
      numberServed = 0;
      totalTimeWaited = 0;
   } // end reset
}
```

Computing the Capital Gain in a Sale of Stock

StockLedger
Responsibilities
Record the shares of a stock purchased, in chronological order
Remove the shares of a stock sold, beginning with the ones held the longest
Compute the capital gain (loss) on shares of a stock sold
Collaborations
Share of stock

A CRC card for the class **`StockLedger`**

Computing the Capital Gain in a Sale of Stock



A diagram of the classes **`StockLedger`** *and* **`StockPurchase`**

StockLedger.java

```
public class StockLedger  {
  private QueueInterface<StockPurchase> ledger;

  public StockLedger()    {
    ledger = new LinkedQueue<>();
  } // end default constructor
```

```
  // Records a stock purchase in this ledger.
  //    sharesBought - The number of shares
  //                   purchased.
  //    pricePerShare - The price per share.
  public void buy(int sharesBought,
                  double pricePerShare)    {
    while (sharesBought > 0)      {
      StockPurchase purchase
            = new StockPurchase(pricePerShare);
      ledger.enqueue(purchase);
      sharesBought--;
    }
  } // end buy
```

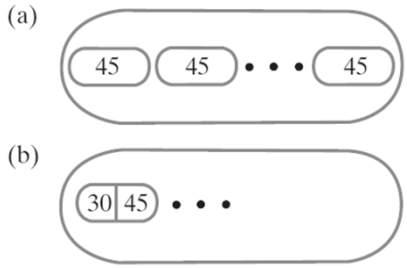
```
  // Removes from this ledger any shares that
  // were sold and computes the capital gain or
  // loss.
  //    sharesSold     The number of shares sold.
  //    pricePerShare  The price per share.
  //    Returns the capital gain (loss). */
  public double sell(int sharesSold,
                     double pricePerShare)    {
    double saleAmount
                = sharesSold * pricePerShare;
    double totalCost = 0;
```

```
    while (sharesSold > 0)      {
      StockPurchase share = ledger.dequeue();
      double shareCost = share.getCostPerShare();
      totalCost = totalCost + shareCost;
      sharesSold--;
    }

    // Gain or loss
    return saleAmount - totalCost;
  }
}
```

StockPurchase.java

```
//  An immutable class that represents the
//  purchase of one share of stock.
public class StockPurchase  {
      private double cost;

      public StockPurchase(double costPerShare)
      {
            cost = costPerShare;
      } // end constructor

      public double getCostPerShare()     {
            return cost;
      }
}
```

Computing the Capital Gain in a Sale of Stock



A queue of :
(a) *individual shares of stock;*
(b) *grouped shares*

Java Class Library: The Interface `Queue`

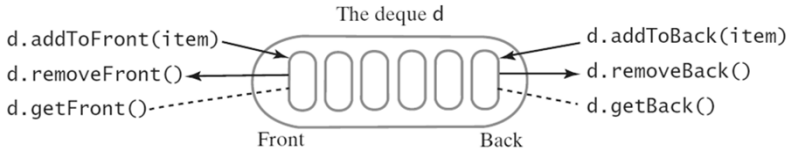
Methods provided

- **`add`**
- **`offer`**
- **`remove`**
- **`poll`**
- **`element`**
- **`peek`**
- **`isEmpty`**
- **`size`**

The ADT Deque

- A double ended queue
- *Deque* pronounced “deck”
- Has both queuelike operations and stacklike operations

The ADT Deque



An instance d *of a deque*

DequeInterface.java

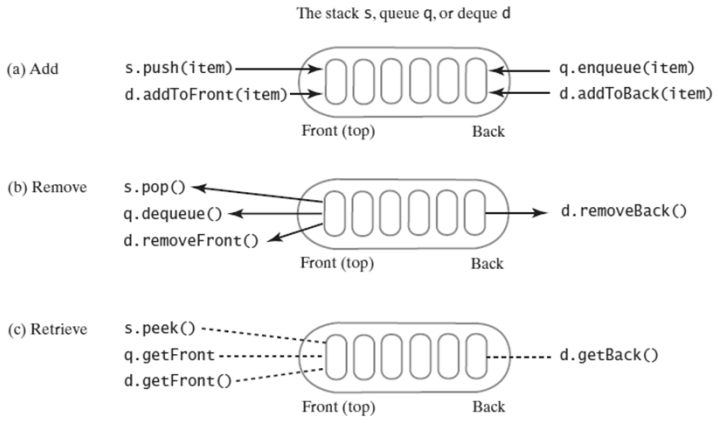
```
//  An interface for the ADT deque.

public interface DequeInterface<T>  {
   // Adds a new entry to the front/back of this
   // dequeue.
   // newEntry - An object to be added
   public void addToFront(T newEntry);
   public void addToBack(T newEntry);
```

```
// Removes and returns the front/back entry of
// this dequeue.
// Returns - the object at the front/back of
// the dequeue.
// Throws  EmptyQueueException if the dequeuer
// is empty before the operation
public T removeFront();
public T removeBack();
```

```
// Retrieves the front/back entry of this
// dequeue.
// Returns - the object at the front/back
// of the dequeue.
// Throws  EmptyQueueException if the dequeuer
// is empty before the operation
public T getFront();
public T getBack();
```

```
   // Detects whether this dequeue is empty.
   // Returns - true if the queue is empty,
   // or false otherwise
   public boolean isEmpty();

   //  Removes all entries from this dequeue
   public void clear();
}
```

The ADT Deque



A comparison of operations for a stack *s*, a queue *q*, and a deque *d*: (a) add; (b) remove; (c) retrieve

The ADT Deque

```
// Read a line
d = a new empty deque
while (not end of line)
{
   character = next character read
   if (character == ←)
      d.removeBack()
   else
      d.addToBack(character)
}
// Display the corrected line
while (!d.isEmpty())
   System.out.print(d.removeFront())
System.out.println()
```

DequeInterface.java

```
// An interface for the ADT deque.

public interface DequeInterface<T>  {
   // Adds a new entry to the front/back of
   // this dequeue.
   // newEntry -  An object to be added
   public void addToFront(T newEntry);
   public void addToBack(T newEntry);
```

```
// Removes and returns the front/back entry
// of this dequeue
// Returns - the object at the front/back of
//           the dequeue
// Throws  EmptyQueueException if the dequeuer
//         is empty before the operation
public T removeFront();
public T removeBack();
```

```
// Retrieves the front/back entry of this
// dequeue.
// Returns - the object at the front/back of
/            the dequeue.
// Throws  EmptyQueueException if the dequeuer
//         is empty before the operation
public T getFront();
public T getBack();
```

```
   //  Detects whether this dequeue is empty.
   //  Returns - true if the queue is empty,
   //  or false otherwise
   public boolean isEmpty();

   //  Removes all entries from this dequeue
   public void clear();
}
```

Computing the Capital Gain in a Sale of Stock

```
// Records a stock purchase in this ledger.
// sharesBought - The number of shares purchased.
// pricePerShare - The price per share
public void buy(int sharesBought,
                double pricePerShare)    {
  StockPurchase purchase = new StockPurchase
                   (sharesBought, pricePerShare);
  ledger.addToBack(purchase);
}
```

Method **buy** *creates an instance of* **StockPurchase** *and places it at the back of the deque*

Computing the Capital Gain in a Sale of Stock

```
//  Removes from this ledger any shares that
//  were sold and computes the capital gain or
//  loss.
//  sharesSold - The number of shares sold
//  pricePerShare - The price per share
//  Returns  The capital gain (loss).
public double sell(int sharesSold,
                   double pricePerShare)  {
  double saleAmount = sharesSold * pricePerShare;
  double totalCost = 0;
```

The method **`sell`** *is more involved*

```
  while (sharesSold > 0)  {
    StockPurchase transaction
                    = ledger.removeFront();
    double shareCost
              = transaction.getCostPerShare();
    int numberOfShares
          = transaction.getNumberOfShares();

    if (numberOfShares > sharesSold)          {
      totalCost = totalCost
               + sharesSold * shareCost;
      int numberToPutBack
            = numberOfShares - sharesSold;
      StockPurchase leftOver = new StockPurchase
                    (numberToPutBack, shareCost);
```

```
      // Return leftover shares
      // Note: Loop will exit since sharesSold
      // will be <= 0 later
      ledger.addToFront(leftOver);
    }
    else
      totalCost = totalCost
             + numberOfShares * shareCost;

    sharesSold = sharesSold - numberOfShares;
  } // end while

  return saleAmount - totalCost; // Gain or loss
}
```

Java Class Library: The Interface **`Deque`**

Methods provided

- **`addFirst, offerFirst`**
- **`addLast, offerLast`**
- **`removeFirst, pollFirst`**
- **`removeLast, pollLast`**
- **`getFirst, peekFirst`**
- **`getLast, peekLast`**
- **`isEmpty, clear, size`**
- **`push, pop`**

ADT Priority Queue

- Consider how a hospital assigns a priority to each patient that *overrides* time at which patient arrived.
- ADT priority queue organizes objects according to their priorities
- Definition of "priority" depends on nature of the items in the queue

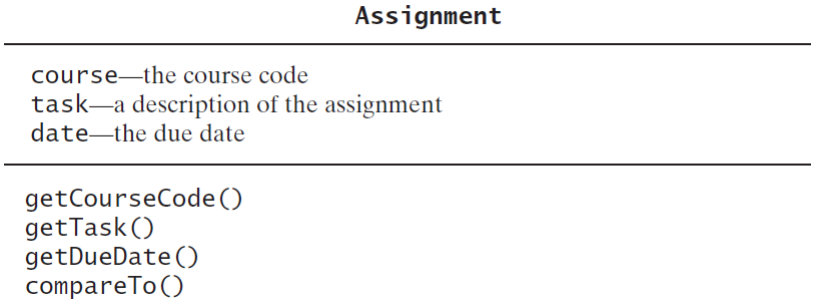
PriorityQueueInterface.java

```
//   An interface for the ADT priority queue.
public interface
  PriorityQueueInterface<T extends
                    Comparable<? super T>> {
  // Adds a new entry to this priority queue
  // newEntry - An object to be added.
  public void add(T newEntry);
```

```
  // Removes and returns the entry having the
  // highest priority
  // Returns - either the object having the
  //       highest priority or, if the priority
  //       queue is empty before the operation,
  //       null
  public T remove();

   // Retrieves the entry having the highest
   // priority
   // Returns - either the object having the
   //           highest priority or, if the
   //           priority queue is empty, null
   public T peek();
```

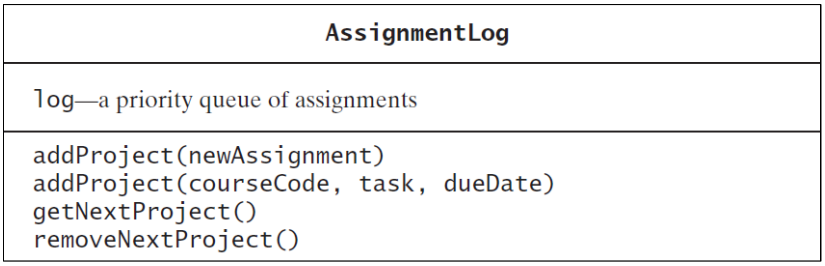
```
  // Detects whether this priority queue is
  // empty
  // Returns - true if the priority queue is
  //           empty, or false otherwise
  public boolean isEmpty();

   // Gets the size of this priority queue
   // Returns - the number of entries currently
   //           in the priority queue
   public int getSize();

   // Removes all entries from this priority
   // queue
   public void clear();
}
```

Tracking Your Assignments



A diagram of the class **`Assignment`**

Tracking Your Assignments



A diagram of the class **`AssignmentLog`**

Tracking Your Assignments

```
import java.sql.Date;
// A class that represents a log of assignments
// ordered by priority.

public class AssignmentLog  {
  private PriorityQueueInterface<Assignment> log;

  public AssignmentLog()    {
    log = new LinkedPriorityQueue<>();
  }
```

The class **`AssignmentLog`**

```
  public void addProject
            (Assignment newAssignment)     {
    log.add(newAssignment);
  }

  public void addProject(String courseCode,
                String task, Date dueDate)    {
    Assignment newAssignment = new Assignment
                      (courseCode, task, dueDate);
    addProject(newAssignment);
  }

  public Assignment getNextProject()   {
    return log.peek();
  }
```

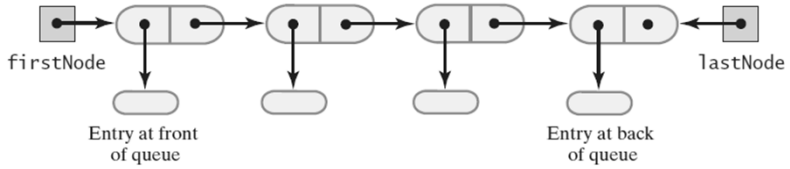
```
    public Assignment removeNextProject()     {
       return log.remove();
    }
}
```

Java Class Library: The Class **`PriorityQueue`**

Basic constructors and methods

- **`PriorityQueue`**
- **`add`**
- **`offer`**
- **`remove`**
- **`poll`**
- **`element`**
- **`peek`**
- **`isEmpty`**, **`clear`**, **`size`**

Linked Implementation of a Queue



A chain of linked nodes that implements a queue

LinkedQueue.java

```
public final class LinkedQueue<T>
          implements QueueInterface<T> {

  // References node at front of queue
  private Node firstNode;
  // References node at back of queue
  private Node lastNode;

  public LinkedQueue()  {
    firstNode = null;
    lastNode = null;
  }
```

An outline of a linked implementation of the ADT queue

The Private class **Node**

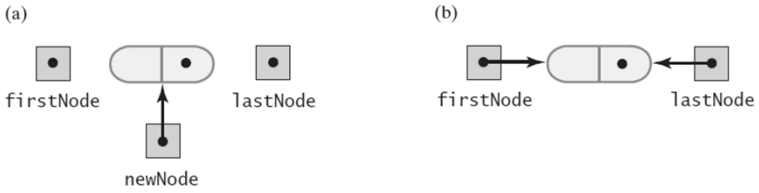
```
private class Node  {
  private T    data; // Entry in queue
  private Node next; // Link to next node

  // Constructors and methods getData, setData,
  // getNxtNode, setNextNode go here
}
```

LinkedQueue.java

```
public void enqueue(T newEntry)     {
  Node newNode = new Node(newEntry, null);

  if (isEmpty())
    firstNode = newNode;
  else
    lastNode.setNextNode(newNode);

  lastNode = newNode;
}
```

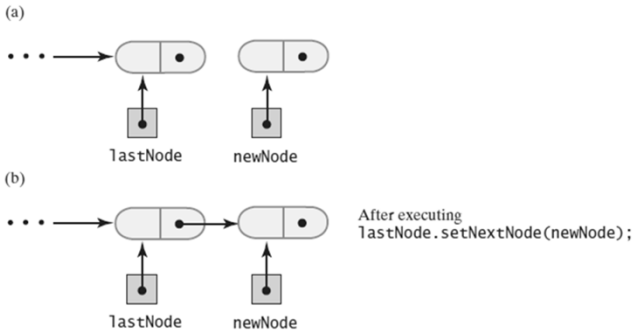
The definition of **enqueue**
Performance is O*(1)*

Linked Implementation of a Queue



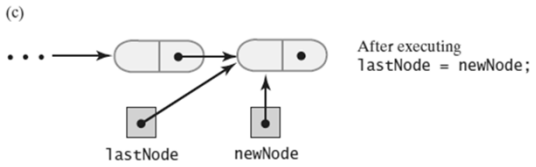
(a) Before adding a new node to an empty chain
(b) After adding it

Linked Implementation of a Queue



(a) Before
(b) During adding a new node to the end of a nonempty chain that has a tail reference

Linked Implementation of a Queue



(c) After adding a new node to the end of a nonempty chain that has a tail reference

Linked Implementation of a Queue

```
public T getFront()     {
  if (isEmpty())
    throw new EmptyQueueException();
  else
     return firstNode.getData();
}
```

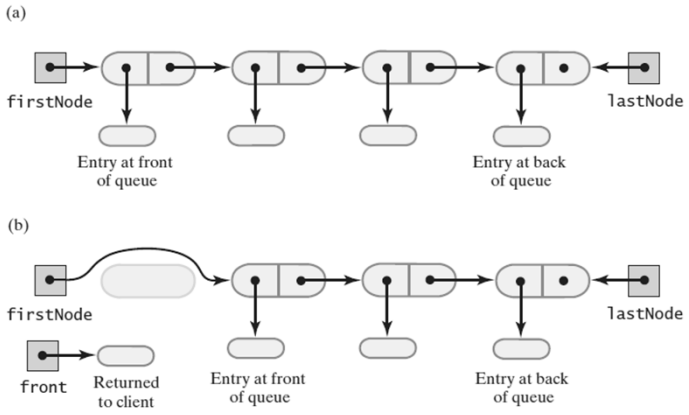
Retrieving the front entry

Linked Implementation of a Queue

```
public T dequeue()  {
  // Might throw EmptyQueueException
  T front = getFront();
  assert firstNode != null;
  firstNode.setData(null);
  firstNode = firstNode.getNextNode();

  if (firstNode == null)
    lastNode = null;

  return front;
}
```

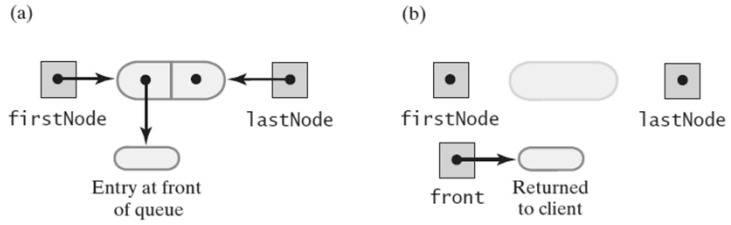
Removing the front entry

Linked Implementation of a Queue



a) A queue of more than one entry
b) After removing the entry at the front of the queue

Linked Implementation of a Queue

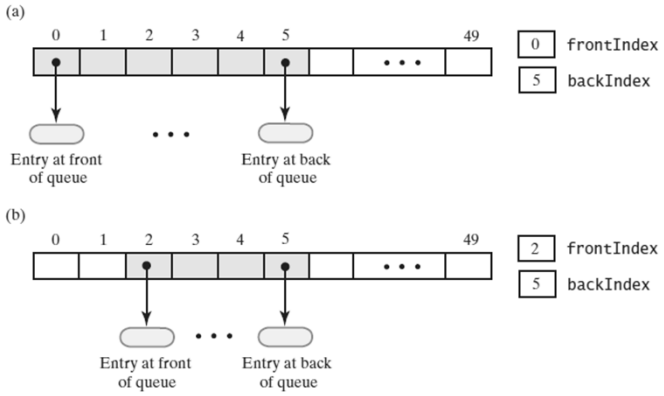


(a) A queue of one entry;
(b) After removing the entry at the front of the queue

```
public boolean isEmpty()       {
  return (firstNode == null)
               && (lastNode == null);
}
      public void clear()
      {
            firstNode = null;
            lastNode = null;
      }
```

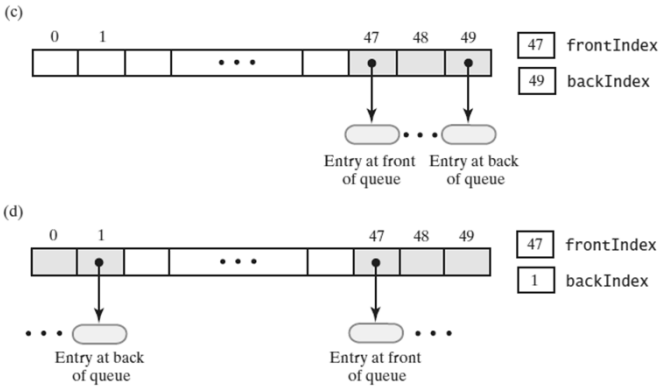
Public methods **`isEmpty`** *and* **`clear`**

Array-Based Implementation of a Queue: Circular Array



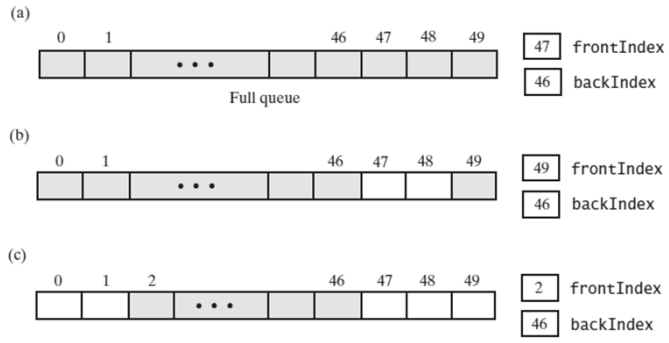
An array that represents a queue without moving any entries:
(a) initially
(b) after removing the entry at the front twice

Circular Queue



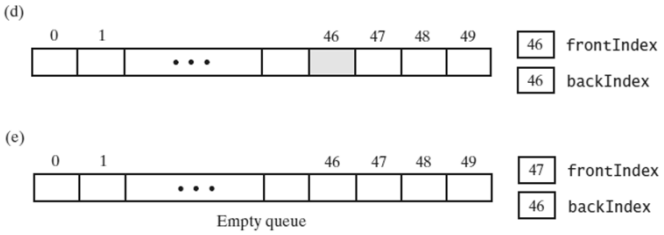
An array that represents a queue without moving any entries:
(c) several more additions, removals;
(d) after two additions that wrap around to beginning of array

Circular Array



A circular array that represents a queue:
(a) when full
(b) after removing two entries
(c) after removing three more entries

Circular Array



A circular array that represents a queue:
(d) after removing all but one entry
(e) after removing the remaining entry

ArrayQueue.java

```
// A class that implements the ADT queue by using
// an expandable circular array with one unused
// location after the back of the queue.

public final class ArrayQueue<T>
              implements QueueInterface<T> {
  // Circular array of queue entries and one
  // unused location
  private T[] queue;
  private int frontIndex; // Index of front entry
  private int backIndex;  // Index of back entry
  private boolean initialized = false;
  private static final int DEFAULT_CAPACITY = 3;
  private static final int MAX_CAPACITY = 10000;
```

```
   public ArrayQueue()     {
      this(DEFAULT_CAPACITY);
   }

   public ArrayQueue(int initialCapacity)    {
      checkCapacity(initialCapacity);

      // The cast is safe because the new array
      // contains null entries
      @SuppressWarnings("unchecked")
      T[] tempQueue = (T[])
                new Object[initialCapacity + 1];
      queue = tempQueue;
      frontIndex = 0;
      backIndex = initialCapacity;
      initialized = true;
   }
```

Circular Array with One Unused Location

```
public void enqueue(T newEntry)   {
   checkInitialization();
   ensureCapacity();
   backIndex
      = (backIndex + 1) % queue.length;
   // Index of location after current
   // back of queue
   queue[backIndex] = newEntry;
 }
```

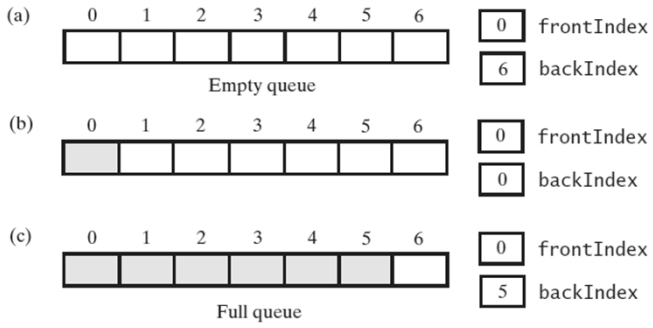
Adding to the back

Circular Array with One Unused Location

```
public T getFront()   {
  checkInitialization();
  if (isEmpty())
    throw new EmptyQueueException();
  else
    return queue[frontIndex];
}
```

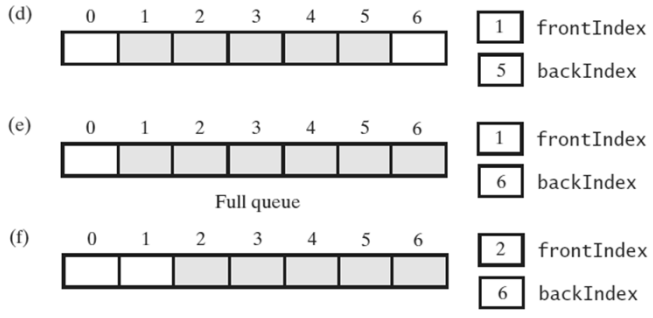
Retrieving the front entry

Circular Array with One Unused Location



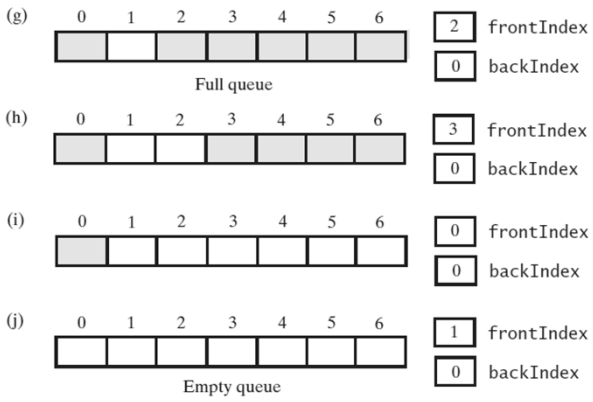
A seven-location circular array that contains at most six entries of a queue

Circular Array with One Unused Location



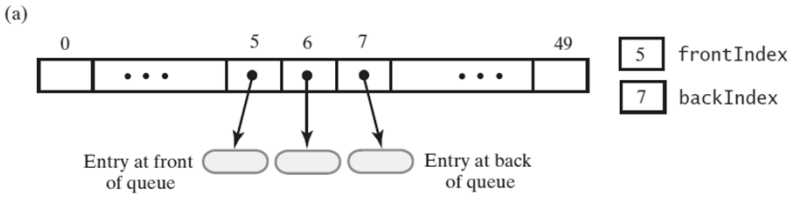
A seven-location circular array that contains at most six entries of a queue

Circular Array with One Unused Location



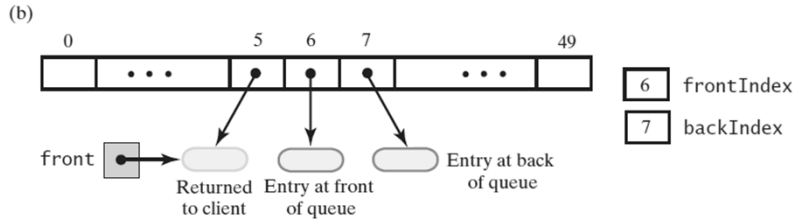
A seven-location circular array that contains at most six entries of a queue

Circular Array with One Unused Location



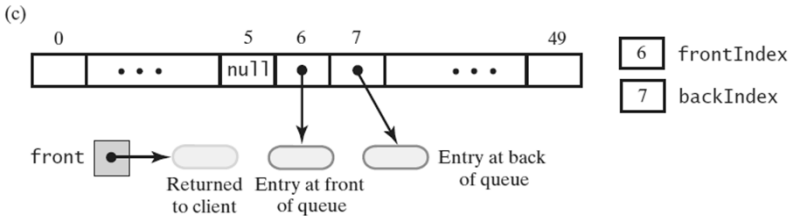
An array-based queue: (a) *initially*

Circular Array with One Unused Location



An array-based queue: (b) *after removing its front entry by incrementing* **`frontIndex`**;

Circular Array with One Unused Location



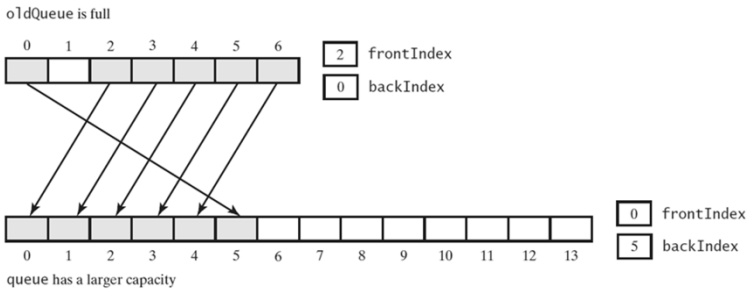
An array-based queue: (c) *after removing its front entry by setting* **`queue[frontIndex]`** *to null and then incrementing* **`frontIndex`**

Circular Array with One Unused Location

```
public T dequeue()  {
  checkInitialization();
  if (isEmpty())
    throw new EmptyQueueException();
  else  {
    T front = queue[frontIndex];
    queue[frontIndex] = null;
    // Index of new front of queue
    frontIndex
            = (frontIndex + 1) % queue.length;
    return front;
  }
}
```

Implementation of **dequeue**

Circular Array with One Unused Location



Doubling the size of an array-based queue

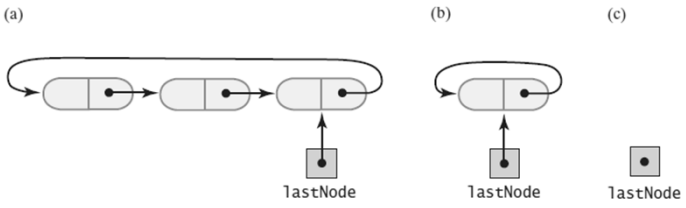
ensureCapacity()

```
// Doubles the size of the array queue
// if it is full.
// Precondition: checkInitialization has been
// called.
private void ensureCapacity()   {
  if (frontIndex
        == ((backIndex + 2) % queue.length)) {
  // If array is full , double size of array
  T[] oldQueue = queue;
  int oldSize = oldQueue.length;
  int newSize = 2 * oldSize;
```

```
  // Queue capacity is 1 fewer than array
  // length
  checkCapacity(newSize - 1);

  // The cast is safe because the new array
  // contains null entries
  @SuppressWarnings("unchecked")
  T[] tempQueue = (T[]) new Object[newSize];
  queue = tempQueue;

  // Number of queue entries = oldSize - 1
  // index of last entry = oldSize - 2
  for (int index = 0; index < oldSize - 1;
                                index++)     {
    queue[index] = oldQueue[frontIndex];
    frontIndex = (frontIndex + 1) % oldSize;
  }
```

```
    frontIndex = 0;
    backIndex = oldSize - 2;
  }
}

  public boolean isEmpty()  {
    return frontIndex ==
          ((backIndex + 1) % queue.length);
  } // end isEmpty
```

Circular Linked Implementations of a Queue

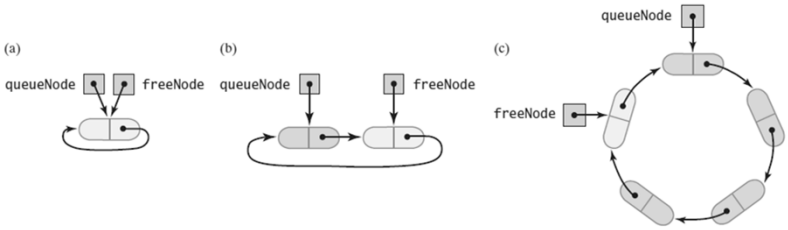


A circular linked chain with an external reference to its last node that
(a) has more than one node
(b) has one node
(c) is empty

Two-Part Circular Linked Chain

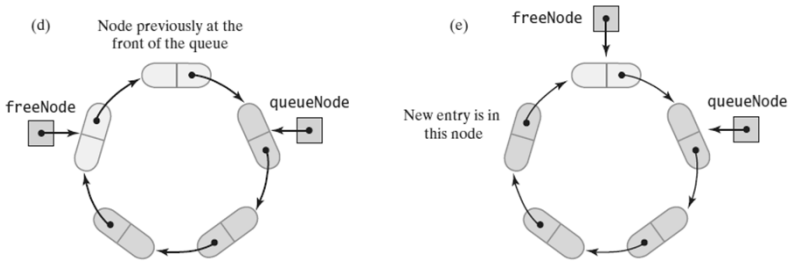
A two-part circular linked chain that represents both a queue and the nodes available to the queue

Two-Part Circular Linked Chain



A two-part circular linked chain that represents a queue:
(a) when it is empty
(b) after adding one entry;
(c) after adding three more entries

Two-Part Circular Linked Chain



A two-part circular linked chain that represents a queue:
(d) after removing the front entry;
(e) after adding one more entry

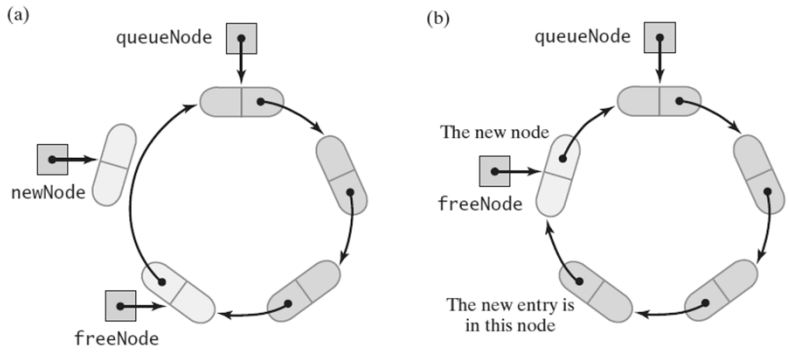
Two-Part Circular Linked Chain

```
// A class that implements the ADT queue by
// using a two-part circular chain of nodes

public final class TwoPartCircularLinkedQueue<T>
                   implements QueueInterface<T> {
  // References first node in queue
  private Node queueNode;

  // References node after back of queue
  private Node freeNode;
```

```
  public TwoPartCircularLinkedQueue()     {
      freeNode = new Node(null, null);
      freeNode.setNextNode(freeNode);
      queueNode = freeNode;
  } // end default constructor

  // Implementations of queue operations follow
  //  below…
```

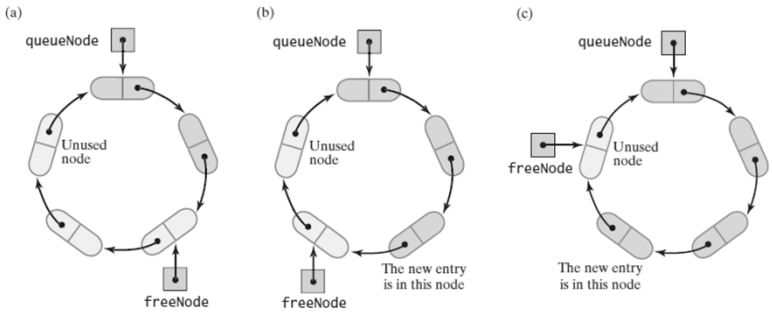
```
  private class Node    {
     private T    data;  // Queue entry
    private Node next;  // Link to next node
  }
} // end TwoPartCircularLinkedQueue
```

Two-Part Circular Linked Chain



A chain that requires a new node for an addition to a queue:
(a) before the addition;
(b) (b) after the addition

Two-Part Circular Linked Chain



(a) A chain with nodes available for additions to a queue
(b) the chain after one addition
(c) the chain after another addition

Two-Part Circular Linked Chain

```
public void enqueue(T newEntry)    {
   freeNode.setData(newEntry);

   if (isChainFull())  {
   // Allocate a new node and insert it after
   // the node that freeNode references
     Node newNode = new Node(null,
                     freeNode.getNextNode());
     freeNode.setNextNode(newNode);
   } // end if

   // Order O(1)
   freeNode = freeNode.getNextNode();
 }
```

```
public T getFront()  {
   if (isEmpty())
     throw new EmptyQueueException();
   else
     return queueNode.getData();
 }

 public T dequeue()  {
   // Might throw EmptyQueueException
   T front = getFront();
   assert !isEmpty();

   queueNode.setData(null);
   queueNode = queueNode.getNextNode();
   return front;
 }
```

```
public boolean isEmpty()  {
  return queueNode == freeNode;
} // end isEmpty

private boolean isChainFull()  {
  return queueNode == freeNode.getNextNode();
}
```

Java Class Library: The Class **`AbstractQueue`**

```
public boolean add(T newEntry)
public boolean offer(T newEntry)
public T remove()
public T poll()
public T element()
public T peek()
public boolean isEmpty()
public void clear()
public int size()
```

Doubly Linked Implementation of a Deque

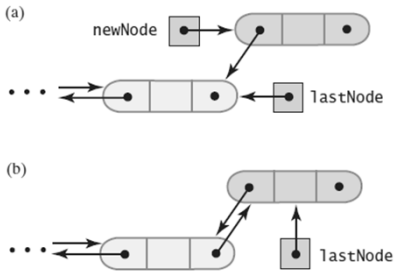
```
public class LinkedDeque<T>
          implements DequeInterface<T>  {

  // References node at front of deque
  private DLNode firstNode;
  // References node at back of deque
  private DLNode lastNode;

  public LinkedDeque()  {
    firstNode = null;
    lastNode = null;
  }
        // Deque operations go here
```

```
  private class DLNode  {
    private T      data;       // Deque entry
    private DLNode next;   // Link to next node
    private DLNode previous; // Link to previous
                             // node

  // Constructors, accessors and mutators go here
  }
}
```

addToBack()

```
public void addToBack(T newEntry)  {
  DLNode newNode
       = new DLNode(lastNode, newEntry, null);

  if (isEmpty())
    firstNode = newNode;
  else
    lastNode.setNextNode(newNode);

  lastNode = newNode;
}
```

Doubly Linked Implementation of a Deque



Adding to the back of a nonempty deque:
(a) after the new node is allocated;
(b) after the addition is complete

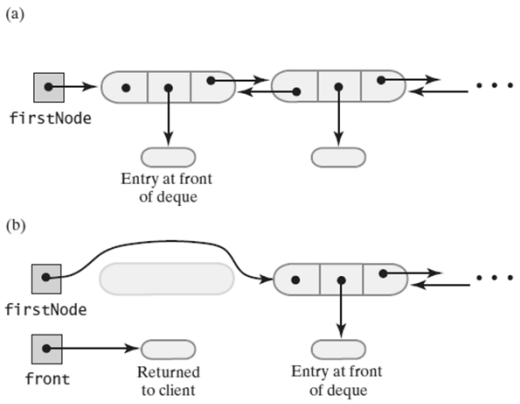
addToFront()

```
public void addToFront(T newEntry) {
  DLNode newNode
      = new DLNode(null, newEntry, firstNode);

  if (isEmpty())
    lastNode = newNode;
  else
    firstNode.setPreviousNode(newNode);

  firstNode = newNode;
}
```

addToFront()

```
public T removeFront()  {
  // Might throw EmptyQueueException
  T front = getFront();

  assert (firstNode != null);
  firstNode = firstNode.getNextNode();

  if (firstNode == null)
    lastNode = null;
  else
    firstNode.setPreviousNode(null);

  return front;
}
```

Doubly Linked Implementation of a Deque

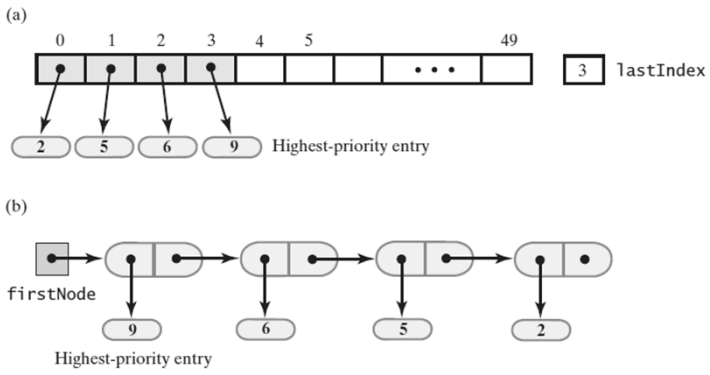


(a) A deque containing at least two entries;
(b) after removing the first node and obtaining a reference to the deque's new first entry.

`removeBack()` – O(1)

```
public T removeBack()  {
  // Might throw EmptyQueueException
  T back = getBack();

  assert (lastNode != null);
  lastNode = lastNode.getPreviousNode();

  if (lastNode == null)
    firstNode = null;
  else
    lastNode.setNextNode(null);

  return back;
}
```

Doubly Linked Implementation of a Deque



Two possible implementations of a priority queue using
(a) an array;
(b) a chain of linked nodes