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CS 106B

Handout #33
February 11, 2015

Implementing Queues

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Outline

- Chapter 14 presents complete implementations for three of the ADTs you've been using since the second assignment: stacks, queues, and vectors. We described one implementation of the **`Stack`** class in Monday's lecture.
- The textbook presents two different strategies to represent the **`Stack`** and **`Queue`** classes: one that uses an array to store the elements and one that uses a linked list. For each of these strategies, implementing a **`Stack`** turns out to be much easier.
- In today's lecture, I am going to focus on implementing the **`Queue`** class, leaving the details of implementing the **`Stack`** and **`Vector`** classes to the text.

Methods in the `Queue<x>` Class

`queue.size()` Returns the number of values in the queue.
`queue.isEmpty()` Returns **`true`** if the queue is empty.
`queue.enqueue(value)` Adds a new value to the end of the queue (which is called its ***tail***).
`queue.dequeue()` Removes and returns the value at the front of the queue (which is called its ***head***).
`queue.peek()` Returns the value at the head of the queue without removing it.
`queue.clear()` Removes all values from the queue.

The `queue.h` Interface

```
/*
 * File: queue.h
 * -------------
 * This interface defines a general queue abstraction that uses
 * templates so that it can work with any element type.
 */

#ifndef _queue_h
#define _queue_h

/*
 * Template class: Queue<ValueType>
 * --------------------------------
 * This class template models a queue, which is a linear collection
 * of values that resemble a waiting line.  Values are added at
 * one end of the queue and removed from the other.  The fundamental
 * operations are enqueue (add to the tail of the queue) and dequeue
 * (remove from the head of the queue).  Because a queue preserves
 * the order of the elements, the first value enqueued is the first
 * value dequeued.  Queues therefore operate in a first-in-first-out
 * (FIFO) order.  For maximum generality, the Queue class is defined
 * using a template that allows the client to define a queue that
 * contains any type of value, as in Queue<string> or Queue<taskT>.
 */
```

The `queue.h` Interface

```
template <typename ValueType>
class Queue {

public:

/*
 * Constructor: Queue
 * Usage: Queue<ValueType> queue;
 * ------------------------------
 * Initializes a new empty queue containing the specified value type.
 */

   Queue();

/*
 * Destructor: ~Queue
 * ------------------
 * Deallocates any heap storage associated with this queue.
 */

   ~Queue();
```

The `queue.h` Interface

```
/*
 * Method: size
 * Usage: int nElems = queue.size();
 * ---------------------------------
 * Returns the number of elements in this queue.
 */

    int size();

/* . . . */

    bool isEmpty();

/* . . . */

    void clear();

/* . . . */

    void enqueue(ValueType value);

/* . . . */

    ValueType dequeue();

/* . . . */

    ValueType peek();
```

The `queue.h` Interface

```
/* Private section */

Private section goes here.

};

/*
 * The template feature of C++ works correctly only if the compiler
 * has access to both the interface and the implementation at the
 * same time.  As a result, the compiler must see the code for
 * the implementation at this point, even though that code is
 * not something that the client needs to see in the interface.
 * Using the #include facility of the C++ preprocessor allows the
 * compiler to have access to the code without forcing the client
 * to wade through the details.
 */

Implementation section goes here.

#endif
```

An Overly Simple Strategy

- The most straightforward way to represent the elements of a queue is to store the elements in an array, exactly as in the **`Stack`** class from Monday.
- Given this representation, the **`enqueue`** operation is extremely simple to implement. All you need to do is add the element to the end of the array and increment the element count. That operation runs in $O(1)$ time.
- The problem with this simplistic approach is that the **`dequeue`** operation requires removing the element from the beginning of the array. If you're relying on the same strategy you used in the array-based editor, implementing this operation requires moving all the remaining elements to fill the hole left by the dequeued element. That operation therefore takes $O(N)$ time.

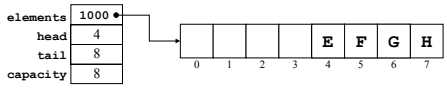
Fixing the $O(N)$ Problem

- The key to fixing the problem of having **`dequeue`** take $O(N)$ time is to eliminate the need for any data motion by keeping track of two indices: one to mark the head of the queue and another to mark the tail.
- Given these two indices, the **`enqueue`** operation stores the new element at the position marked by the **`tail`** index and then increments **`tail`** so that the next element is enqueued into the next slot. The **`dequeue`** operation is symmetric. The next value to be dequeued appears at the array position marked by the **`head`** index. Removing it is then simply a matter of incrementing **`head`**.
- Unfortunately, this strategy typically ends up filling the array space even when the queue itself contains very few elements, as illustrated on the next slide.

Tracing the Array-Based Queue

- Consider what happens if you execute the operations shown.
- Each **`enqueue`** operation adds a value at the tail of the queue.
- Each **`dequeue`** operation takes its result from the head.
- If you continue on in this way, what happens when you reach the end of the array space?

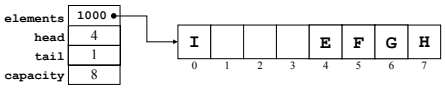
```
Queue<char> queue;
queue.enqueue('A')
queue.enqueue('B')
queue.enqueue('C')
queue.dequeue() → 'A'
queue.enqueue('D')
queue.enqueue('E')
queue.dequeue() → 'B'
queue.enqueue('F')
queue.dequeue() → 'C'
queue.dequeue() → 'D'
queue.enqueue('G')
queue.enqueue('H')
→queue.enqueue('I')
```



Tracing the Array-Based Queue

- At this point, enqueuing the **`I`** would require expanding the array, even though the queue contains only four elements.
- The solution to this problem is to let the elements cycle back to the beginning of the array.

```
Queue<char> queue;
queue.enqueue('A')
queue.enqueue('B')
queue.enqueue('C')
queue.dequeue() → 'A'
queue.enqueue('D')
queue.enqueue('E')
queue.dequeue() → 'B'
queue.enqueue('F')
queue.dequeue() → 'C'
queue.dequeue() → 'D'
queue.enqueue('G')
queue.enqueue('H')
queue.enqueue('I')
```



Implementing the Ring-Buffer Strategy

- The data structure described on the preceding slide is called a ***ring buffer*** because the end of the array is linked back to the beginning.
- The arithmetic operations necessary to implement the ring buffer strategy are easy to code using ***modular arithmetic***, which is simply normal arithmetic in which all values are reduced to a specific range by dividing each result by some constant (in this case, the capacity of the array) and taking the remainder. In C++, you can use the **`%`** operator to implement modular arithmetic.
- When you are using the ring-buffer strategy, it is typically necessary to expand the queue when there is still one free element left in the array. If you don't do so, the simple test for an empty queue—whether **`head`** is equal to **`tail`**—fails because that would also be true in a completely full queue.

Structure for the Array-Based Queue

```
/*
 * Implementation notes
 * --------------------
 * The array-based queue stores the elements in a ring buffer, which
 * consists of a dynamic index and two indices: head and tail.  Each
 * index wraps to the beginning if necessary.  This design requires
 * that there is always one unused element in the array.  If the queue
 * were allowed to fill completely, the head and tail indices would
 * have the same value, and the queue will appear empty.
 */

private:

   static const int INITIAL_CAPACITY = 10;

/* Instance variables */

   ValueType *array;                    /* A dynamic array of the elements */
   int capacity;                        /* The allocated size of the array */
   int head;                            /* The index of the head element   */
   int tail;                            /* The index of the tail element   */

/* Private method prototypes */

   void expandCapacity();
```

Code for the Ring-Buffer Queue

```
/* Implementation section */

/*
 * Implementation notes: Queue constructor
 * ---------------------------------------
 * The constructor must allocate the array storage for the queue
 * elements and initialize the fields of the object.
 */

template <typename ValueType>
Queue<ValueType>::Queue() {
   capacity = INITIAL_CAPACITY;
   array = new ValueType[capacity];
   head = 0;
   tail = 0;
}

/*
 * Implementation notes: ~Queue destructor
 * ---------------------------------------
 * The destructor frees any memory that is allocated by the implementation.
 */

template <typename ValueType>
Queue<ValueType>::~Queue() {
   delete[] array;
}
```

Code for the Ring-Buffer Queue

```
/*
 * Implementation notes: size
 * --------------------------
 * The size of the queue can be calculated from the head and tail
 * indices by using modular arithmetic.
 */

template <typename ValueType>
int Queue<ValueType>::size() {
   return (tail + capacity - head) % capacity;
}

/*
 * Implementation notes: isEmpty
 * -----------------------------
 * The queue is empty whenever the head and tail indices are
 * equal.  Note that this interpretation means that the queue
 * cannot be allowed to fill the capacity entirely and must
 * always leave one unused space.
 */

template <typename ValueType>
bool Queue<ValueType>::isEmpty() {
   return head == tail;
}
```

Code for the Ring-Buffer Queue

```
/*
 * Implementation notes: clear
 * ---------------------------
 * The clear method need not take account of where in the
 * ring buffer any existing data is stored and can simply
 * set the head and tail index back to the beginning.
 */

template <typename ValueType>
void Queue<ValueType>::clear() {
   head = tail = 0;
}

/*
 * Implementation notes: enqueue
 * -----------------------------
 * This method must first check to see whether there is
 * enough room for the element and expand the array storage
 * if necessary.
 */

template <typename ValueType>
void Queue<ValueType>::enqueue(ValueType value) {
   if (size() == capacity - 1) expandCapacity();
   array[tail] = value;
   tail = (tail + 1) % capacity;
}
```

Code for the Ring-Buffer Queue

```
/*
 * Implementation notes: dequeue, peek
 * -----------------------------------
 * These methods must check for an empty queue and report an
 * error if there is no first element.
 */

template <typename ValueType>
ValueType Queue<ValueType>::dequeue() {
   if (isEmpty()) error("dequeue: Attempting to dequeue an empty queue");
   ValueType result = array[head];
   head = (head + 1) % capacity;
   return result;
}

template <typename ValueType>
ValueType Queue<ValueType>::peek() {
   if (isEmpty()) error("peek: Attempting to peek at an empty queue");
   return array[head];
}
```

Code for the Ring-Buffer Queue

```
/*
 * Implementation notes: expandCapacity
 * ------------------------------------
 * This private method doubles the capacity of the elements array
 * whenever it runs out of space.  To do so, it must allocate a new
 * array, copy all the elements from the old array to the new one,
 * and free the old storage.  Note that this implementation also
 * shifts all the elements back to the beginning of the array.
 */

template <typename ValueType>
void Queue<ValueType>::expandCapacity() {
   int count = size();
   int oldCapacity = capacity;
   capacity *= 2;
   ValueType *oldArray = array;
   array = new ValueType[capacity];
   for (int i = 0; i < count; i++) {
      array[i] = oldArray[(head + i) % oldCapacity];
   }
   head = 0;
   tail = count;
   delete[] oldArray;
}

#endif
```

Implementing a Linked-List Queue

- In some ways, the linked-list implementation of a queue is easier to understand than the ring-buffer model, even though it contains pointers.
- In the linked-list version, the private data structure for the **`Queue`** class requires two pointers to cells: a **`head`** pointer that indicates the first cell in the chain, and a **`tail`** pointer that indicates the last cell. Because all insertion happens at the tail of the queue, no dummy cell is required.
- The private data structure must also keep track of the number of elements so that the **`size`** method can run in $O(1)$ time.

Structure for the List-Based Queue

```
/*
 * Implementation notes: Queue data structure
 * ------------------------------------------
 * The list-based queue uses a linked list to store the elements
 * of the queue.  To ensure that adding a new element to the tail
 * of the queue is fast, the data structure maintains a pointer to
 * the last cell in the queue as well as the first.  If the queue is
 * empty, both the head pointer and the tail pointer are set to NULL.
 */

private:

/* Type for linked list cell */

   struct Cell {
      ValueType data;                  /* The data value                */
      Cell *link;                      /* Link to the next cell         */
   };

/* Instance variables */

   Cell *head;                         /* Pointer to the cell at the head */
   Cell *tail;                         /* Pointer to the cell at the tail */
   int count;                          /* Number of elements in the queue */
```

Code for the Linked-List Queue

```
/*
 * Implementation notes: Queue constructor
 * ---------------------------------------
 * The constructor must create an empty linked list and then
 * initialize the fields of the object.
 */

template <typename ValueType>
Queue<ValueType>::Queue() {
   head = tail = NULL;
   count = 0;
}

/*
 * Implementation notes: ~Queue destructor
 * ---------------------------------------
 * The destructor frees any memory that is allocated by the implementation.
 * Freeing this memory guarantees the client that the queue abstraction
 * will not "leak memory" in the process of running an application.
 * Because clear frees each element it processes, this implementation
 * of the destructor simply calls that method.
 */

template <typename ValueType>
Queue<ValueType>::~Queue() {
   clear();
}
```

Code for the Linked-List Queue

```
/*
 * Implementation notes: size, isEmpty, clear
 * ------------------------------------------
 * These implementations should be self-explanatory.
 */

template <typename ValueType>
int Queue<ValueType>::size() {
   return count;
}

template <typename ValueType>
bool Queue<ValueType>::isEmpty() {
   return count == 0;
}

template <typename ValueType>
void Queue<ValueType>::clear() {
   while (count > 0) {
      dequeue();
   }
}
```

Code for the Linked-List Queue

```
/*
 * Implementation notes: enqueue
 * -----------------------------
 * This method allocates a new list cell and chains it in
 * at the tail of the queue.  If the queue is currently empty,
 * the new cell must also become the head pointer in the queue.
 */

template <typename ValueType>
void Queue<ValueType>::enqueue(ValueType value) {
   Cell *cp = new Cell;
   cp->data = value;
   cp->link = NULL;
   if (head == NULL) {
      head = cell;
   } else {
      tail->link = cell;
   }
   tail = cell;
   count++;
}
```

Code for the Linked-List Queue

```
/*
 * Implementation notes: dequeue, peek
 * -----------------------------------
 * These methods must check for an empty queue and report an
 * error if there is no first element.  The dequeue method
 * must also check for the case in which the queue becomes
 * empty and set both the head and tail pointers to NULL.
 */

template <typename ValueType>
ValueType Queue<ValueType>::dequeue() {
   if (isEmpty()) error("dequeue: Attempting to dequeue an empty queue");
   Cell *cp = head;
   ValueType result = cp->data;
   head = cp->link;
   if (head == NULL) tail = NULL;
   count--;
   delete cell;
   return result;
}

template <typename ValueType>
ValueType Queue<ValueType>::peek() {
   if (isEmpty()) error("peek: Attempting to peek at an empty queue");
   return head->data;
}
```