The Queue ADT

Objectives

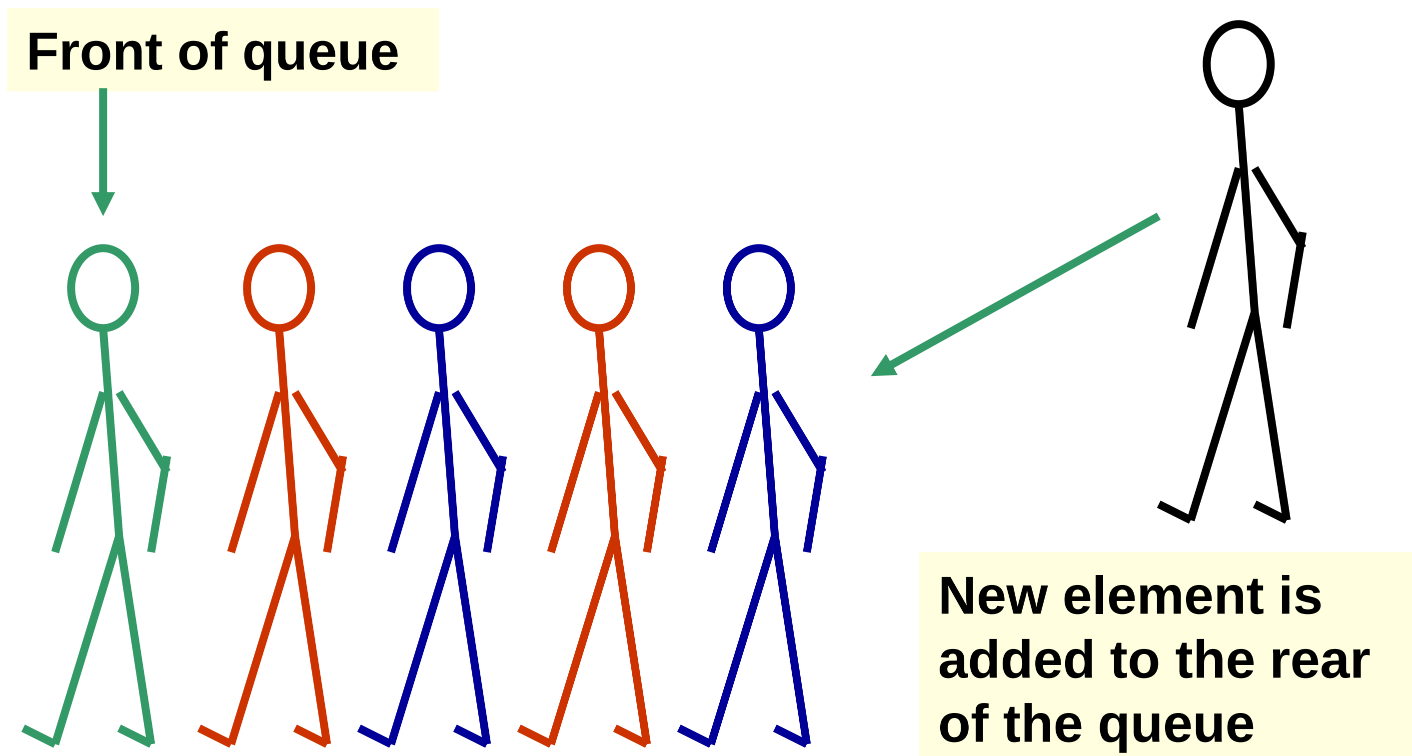
- Define the queue ADT
- Show how a queue can be used to solve problems
- Examine various queue implementations
- Compare queue implementations

Queues

- **Queue**: a linear collection whose elements are added at one end (the ***rear*** or ***tail*** of the queue) and removed from the other end (the ***front*** or ***head*** of the queue)
- A queue is a ***FIFO*** (first in, first out) data structure
- Any waiting line is a queue:
  - The check-out line at a grocery store
  - The cars at a stop light
  - An assembly line

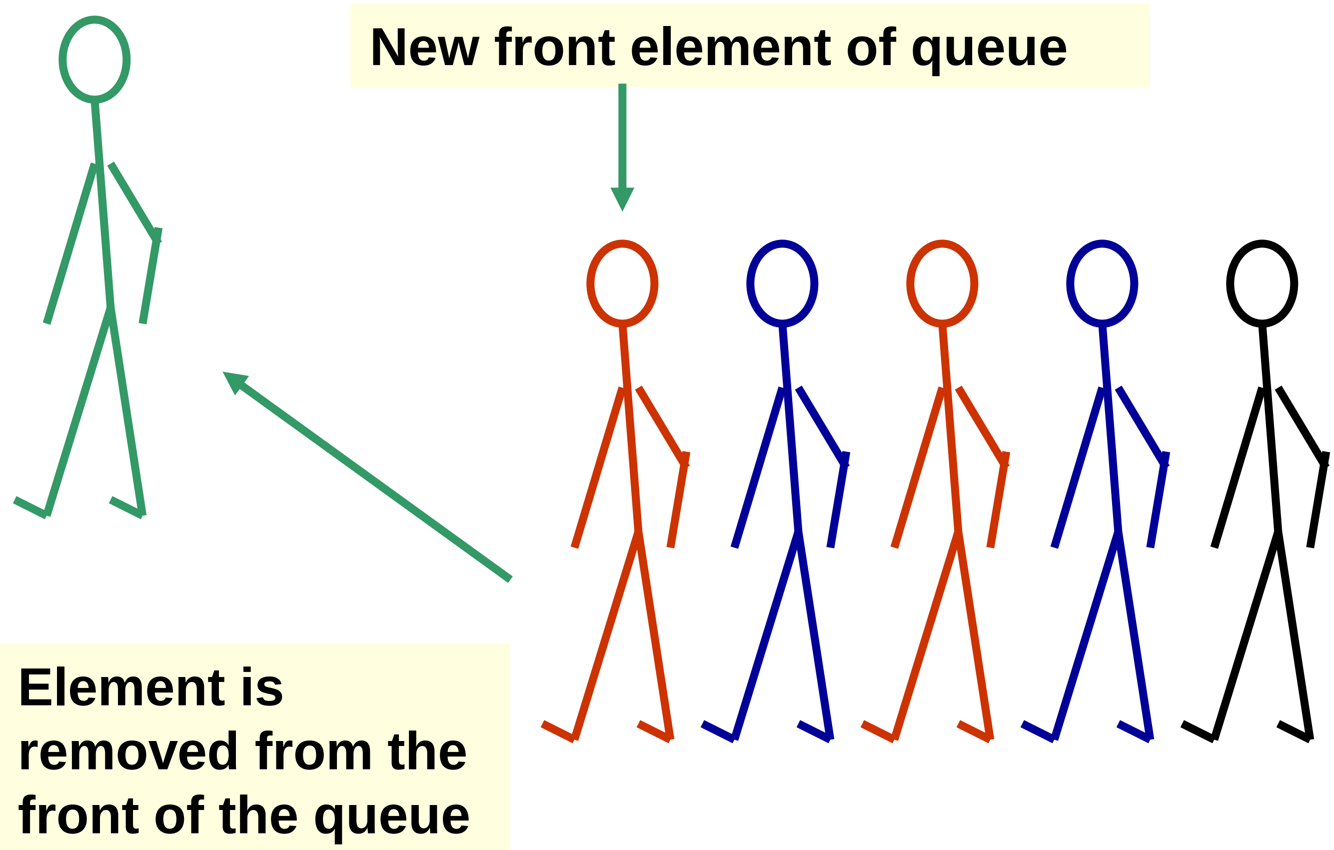
Conceptual View of a Queue

Adding an element



Conceptual View of a Queue

Removing an element



Operations on a Queue

Operation	Description
dequeue	Removes an element from the front of the queue
enqueue	Adds an element to the rear of the queue
first	Examines the element at the front of the queue without removing it
isEmpty	Determines whether the queue is empty
size	Determines the number of elements in the queue
toString	Returns a string representation of the queue

Interface to a Queue in Java

```
public interface QueueADT<T> {
  //  Adds one element to the rear of the queue
  public void enqueue (T element);
  //  Removes and returns the element at the front of the queue
  public T dequeue( ) throws EmptyCollectionE;
  //  Returns without removing the element at the front of the queue
  public T first( ) throws EmptyCollectionE;
  //  Returns true if the queue contains no elements
  public boolean isEmpty( );
  //  Returns the number of elements in the queue
  public int size( );
  //  Returns a string representation of the queue
  public String toString( );
}
```

Uses of Queues in Computing

- Printer queue
- Keyboard input buffer
- GUI event queue (click on buttons, menu items)

Using Queues: Coded Messages

- A ***Caesar cipher*** is a ***substitution code*** that encodes a message by shifting each letter in a message by a constant amount **k**
  - If **k** is **5**, **a** becomes **f**, **b** becomes **g**, etc.
    - ***Example***: ***n qtaj ofaf***
  - Used by Julius Caesar to encode military messages for his generals (around 50 BC)
  - This code is fairly easy to break.

Using Queues: Coded Messages

- ***Modern version***: ROT13
  - Each letter is shifted by 13
  - "used in online forums as a means of hiding spoilers, punchlines, puzzle solutions, and offensive materials from the casual glance" ***(Wikipedia)***

Using Queues: Coded Messages

- ***An improvement***: change how much a letter is shifted depending on where the letter is in the message
- A ***repeating key*** is a sequence of integers that determine how much each character is shifted
  - Example: consider the repeating key

    3 1 7 4 2 5
  - The first character in the message is shifted by 3, the next by 1, the next by 7, and so on
  - When the key is exhausted, start over at the beginning of the key

Using Queues: Coded Messages

A ***repeating key*** is a sequence of integers that determine by how much each character in a message is shifted. Consider the repeating key

3 1 7 4 2 5

a	**b**	**c**	**d**	**e**	**f**	**g**	**h**	**i**	**j**	**k**	**l**	**m**	**n**	**o**	**p**	**q**	**r**	**s**	**t**	**u**	**v**	**w**	**x**	**y**	**z**

message: knowledge

encoded

message:

queue: **3 1 7 4 2 5**

Using Queues: Coded Messages

A ***repeating key*** is a sequence of integers that determine by how much each character in a message is shifted. Consider the repeating key

3 1 7 4 2 5

a	**b**	**c**	**d**	**e**	**f**	**g**	**h**	**i**	**j**	**k**	**l**	**m**	**n**	**o**	**p**	**q**	**r**	**s**	**t**	**u**	**v**	**w**	**x**	**y**	**z**

message: knowledge

encoded

message: n

dequeued: 3

queue: **1 7 4 2 5**

Using Queues: Coded Messages

A ***repeating key*** is a sequence of integers that determine by how much each character in a message is shifted. Consider the repeating key

3 1 7 4 2 5

a	b	c	d	e	f	g	h	i	j	k	l	m	n	o	p	q	r	s	t	u	v	w	x	y	z

message: knowledge

encoded

message: n

queue: **1 7 4 2 5 3**

Using Queues: Coded Messages

A ***repeating key*** is a sequence of integers that determine by how much each character in a message is shifted. Consider the repeating key

3 1 7 4 2 5

a	b	c	d	e	f	g	h	i	j	k	l	m	n	o	p	q	r	s	t	u	v	w	x	y	z

message: knowledge

encoded

message: no

dequeued: 1

queue: **7 4 2 5 3**

Using Queues: Coded Messages

A ***repeating key*** is a sequence of integers that determine by how much each character in a message is shifted. Consider the repeating key

3 1 7 4 2 5

a	b	c	d	e	f	g	h	i	j	k	l	m	n	o	p	q	r	s	t	u	v	w	x	y	z

message: knowledge

encoded

message: no

queue: **7 4 2 5 3 1**

Using Queues: Coded Messages

A ***repeating key*** is a sequence of integers that determine by how much each character in a message is shifted. Consider the repeating key

3 1 7 4 2 5

a	b	c	d	e	f	g	h	i	j	k	l	m	n	o	p	q	r	s	t	u	v	w	x	y	z

message: knowledge

encoded

message: novangjhl

queue: **4 2 5 3 1 7**

Using Queues: Coded Messages

- We can use a queue to store the values of the key
  - ***dequeue*** a key value when needed
  - After using it, ***enqueue*** it back onto the end of the queue

- So, the queue represents the constantly cycling values in the key

Using Queues: Coded Messages

- See ***Codes.java*** in the sample code page of the course's website
  - Note that there are *two* copies of the key, stored in two separate queues
    - The encoder has one copy
    - The decoder has a separate copy
    - Why?

Using Queues: Ticket Counter Simulation

- Simulate the waiting line at a movie theatre:
  - Determine how many cashiers are needed to keep the customer wait time under 7 minutes
- ***Assume***:
  - Customers arrive on average every 15 seconds
  - Processing a request takes two minutes once a customer reaches a cashier
- See ***Customer.java, TicketCounter.java*** in the sample code page of the course's website

Results of Ticket Counter Simulation

Number of Cashiers

1	2	3	4	5	6	7	8	9	10
5317	2325	1332	840	547	355	219	120	120	120

Average time (in seconds)

Queue Implementation Issues

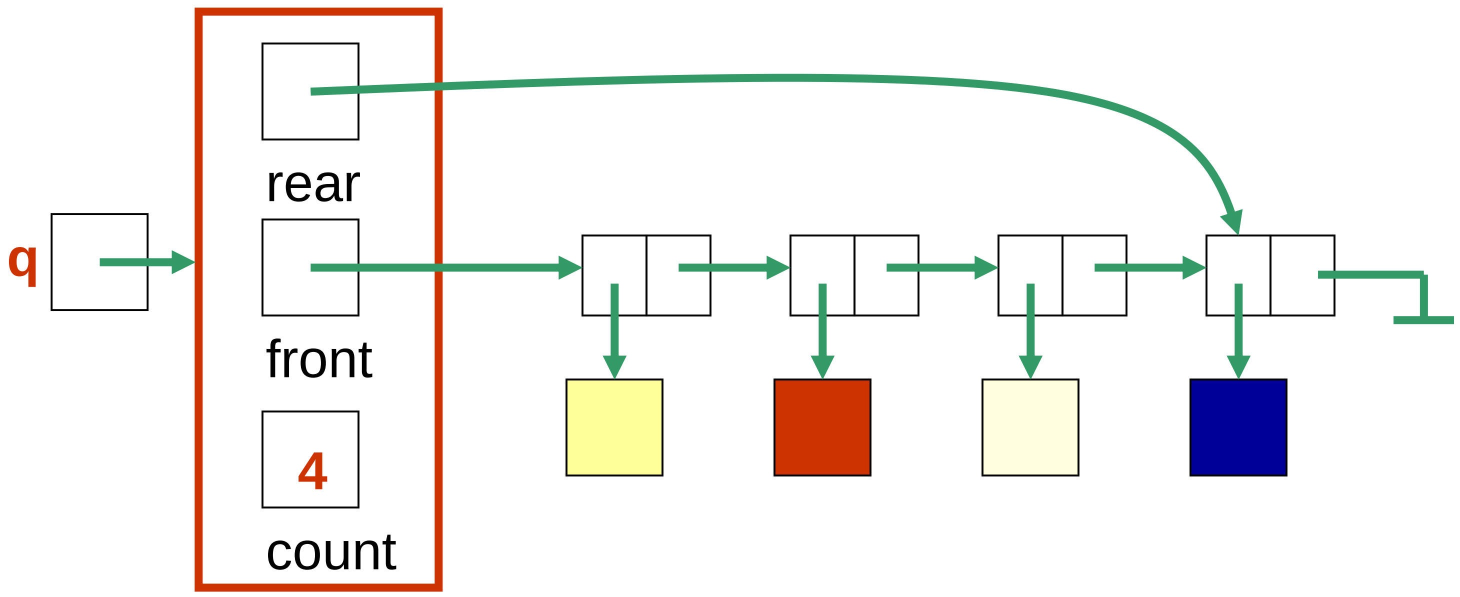
- What do we need to implement a queue?
  - A data structure (***container***) to hold the data elements
  - A variable to indicate the ***front*** of the queue
  - A variable to indicate the ***rear*** of the queue

Queue Implementation Using a Linked List

- A queue can be represented as a ***linked list of nodes***, with each node containing a data item
- We need *two* pointers for the linked list
  - A pointer to the beginning of the linked list (***front*** of queue)
  - A pointer to the end of the linked list (***rear*** of queue)
- We will also have a ***count*** of the number of items in the queue

Linked Implementation of a Queue

A queue q containing four elements



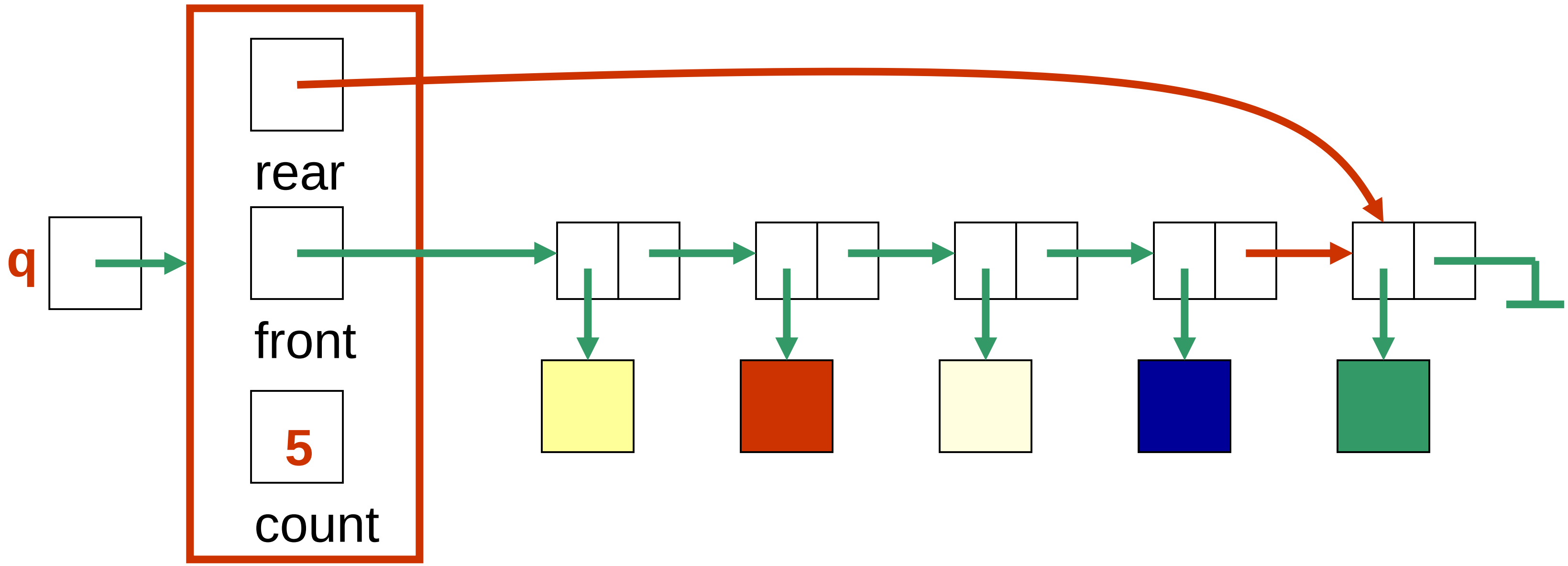
Discussion

- What are the values of front and rear if the queue is empty?

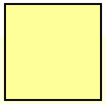
- What are their values if there is only 1 element?

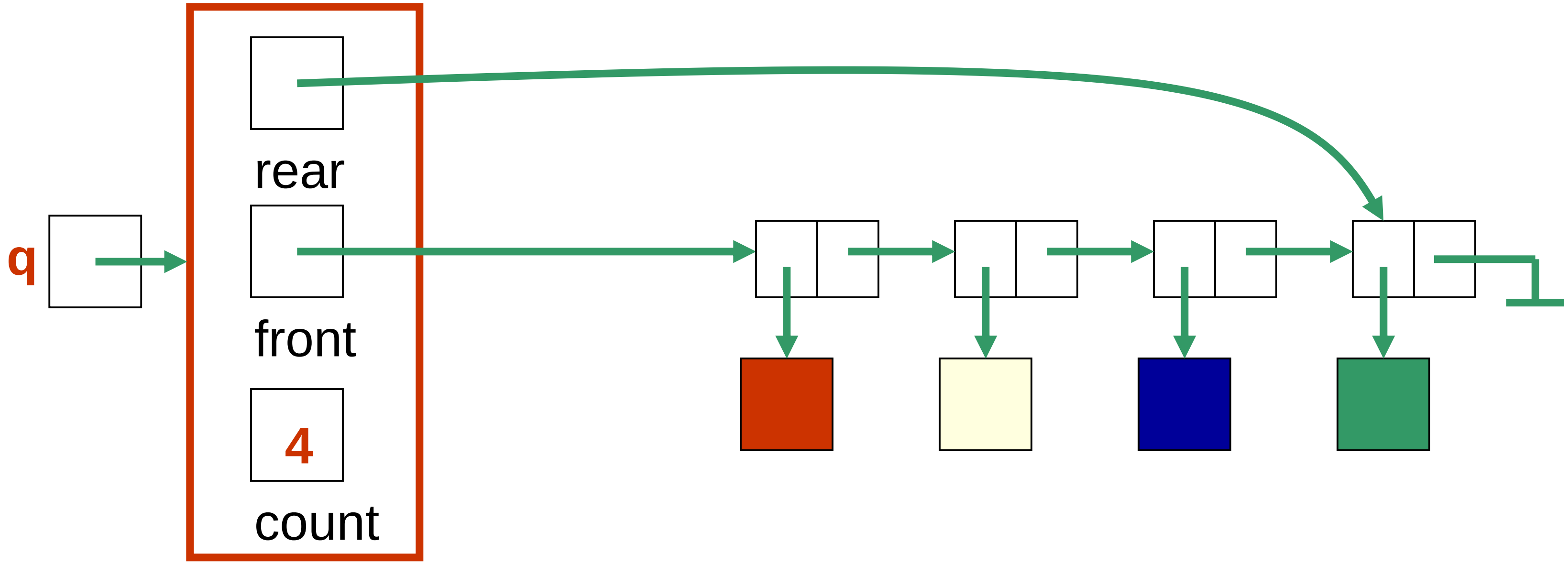
Queue After Adding Element

New element is added in a node at the end of the list, rear points to the new node, and count is incremented



Queue After a **dequeue** Operation

Node containing  is removed from the front of the list (see previous slide), front now points to the node that was formerly second, and count has been decremented.



Java Implementation

- The queue is represented as a linked list of nodes:
  - We will again use the **LinearNode** class
  - **front** is a reference to the head of the queue (beginning of the linked list)
  - **rear** is a reference to the tail of the queue (end of the linked list)
  - The integer **count** is the number of nodes in the queue

```
public class LinkedQueue<T> implements QueueADT<T> {
  /**
   * Attributes
   */
  private int count;
  private LinearNode<T> front, rear;

  /**
   * Creates an empty queue.
   */
  public LinkedQueue() {
    count = 0;
    front = rear = null;
  }
```

```
//-----------------------------------------------------------------
//  Adds the specified element to the rear of the queue.
//-----------------------------------------------------------------
public void enqueue (T element) {
   LinearNode<T> node = new LinearNode<T> (element);

   if (isEmpty( ))
      front = node;
   else
      rear.setNext (node);

   rear = node;
   count++;
}
```

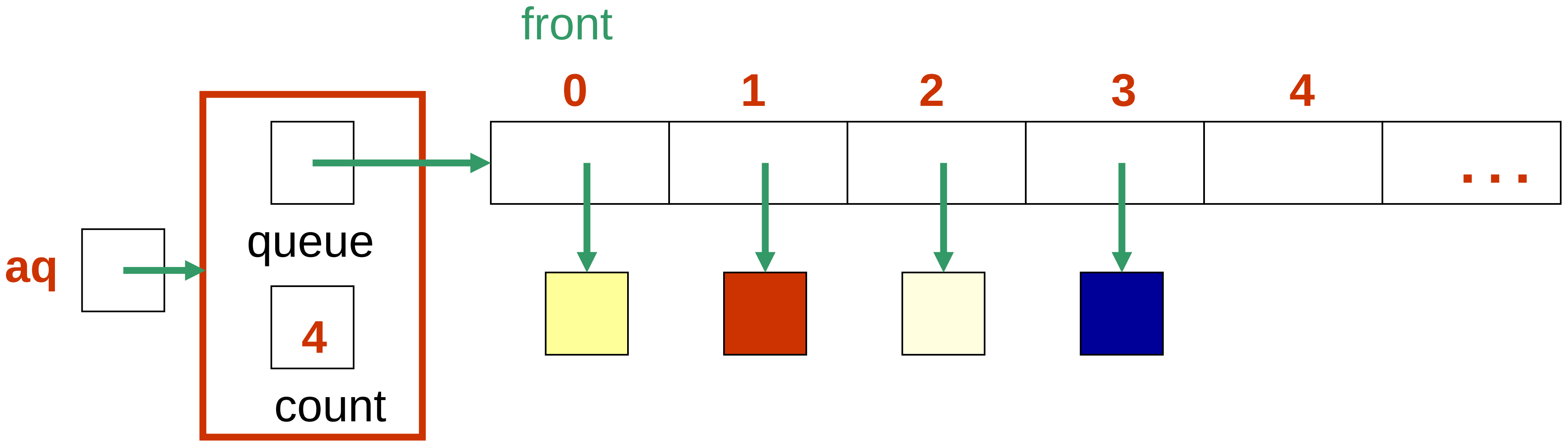
```
//------------------------------------------------------------------
//  Removes the element at the front of the queue and returns a
//  reference to it. Throws an EmptyCollectionException if the
//  queue is empty.
//------------------------------------------------------------------
public T dequeue ( ) throws EmptyCollectionException {
   if (isEmpty( ))
      throw new EmptyCollectionException ("queue");
   T result = front.getElement( );
   front = front.getNext( );
   count--;
   if (isEmpty( ))
      rear = null;
   return result;
}
```

Array Implementation of a Queue

- ***First Approach***:
  - Use an array in which index 0 represents one end of the queue (the *front*)
  - Integer value ***count*** represents the number of elements in the array (so the element at the rear of the queue is in position count - 1)
- ***Discussion***: What is the challenge with this approach?

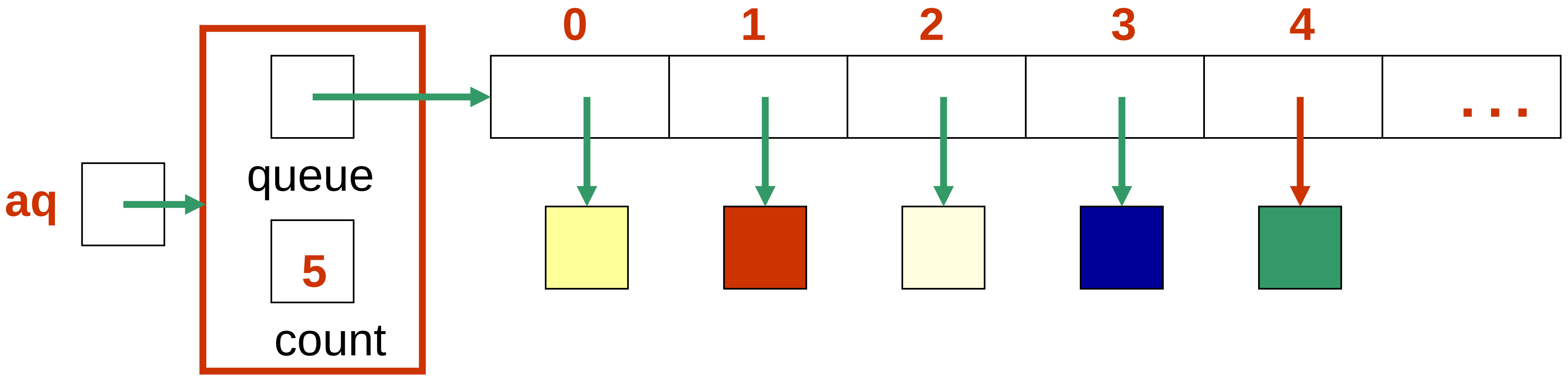
An Array Implementation of a Queue

A queue aq containing four elements

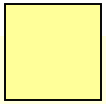


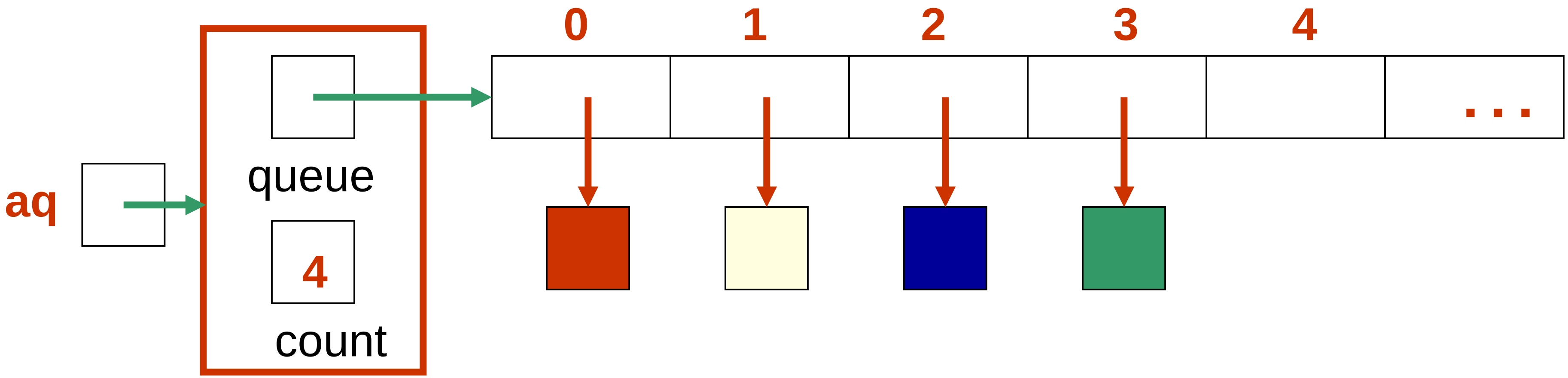
Queue After Adding an Element

The element is added at the array location given by the value of count and then count is increased by 1.



Queue After Removing an Element

Element  **is removed from array location 0, remaining elements are shifted forward one position in the array, and then count is decremented.**



```
public class ArrayQueue<T> implements QueueADT<T> {
  private final int DEFAULT_CAPACITY = 100;
  private int count;
  private T[] queue;

public ArrayQueue() {
    count = 0;
    queue = (T[])(new Object[DEFAULT_CAPACITY]);
  }
public ArrayQueue (int initialCapacity) {
    count = 0;
    queue = (T[])(new Object[initialCapacity]);
  }
```

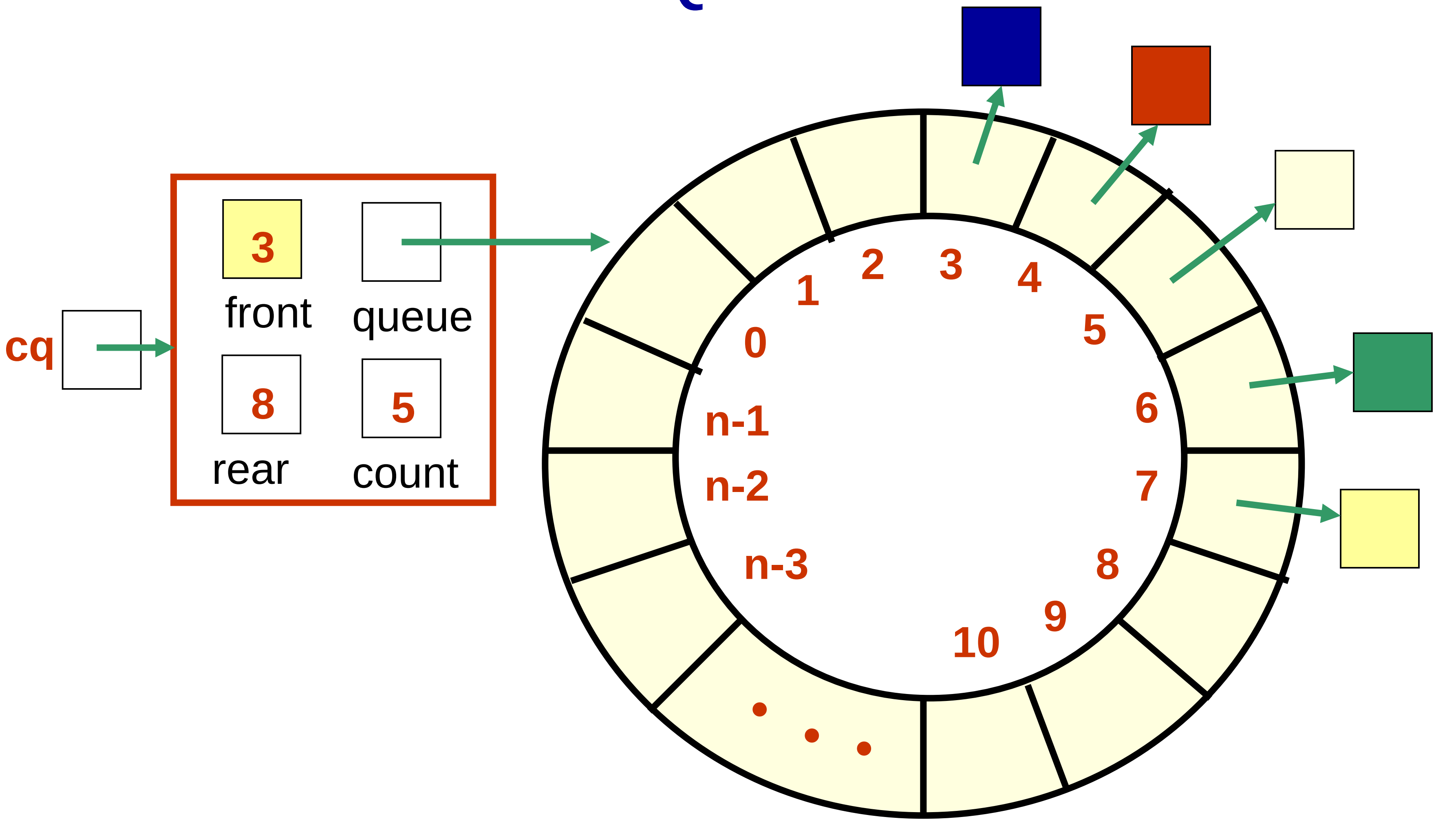
```java
//----------------------------------------------------------------------
//  Adds the specified element to the rear of the queue,
//  expanding the capacity of the queue array if
//  necessary.
//----------------------------------------------------------------------
public void enqueue (T element) {
   if (size() == queue.length)
      expandCapacity( );

   queue[count] = element;
   count++;
}
```

```
//-----------------------------------------------------------------
//  Removes the element at the front of the queue and returns
//  a reference to it. Throws anEmptyCollectionException if the
//  queue is empty.
//-----------------------------------------------------------------
public T dequeue ( ) throws EmptyCollectionException {
   if (isEmpty( ))
      throw new EmptyCollectionException (“Empty queue");
   T result = queue[0];
   count--;
   // shift the elements
   for (int i = 0; i < count; i++)
      queue[i] = queue[i+1];
   queue[count] = null;
   return result;
}
```

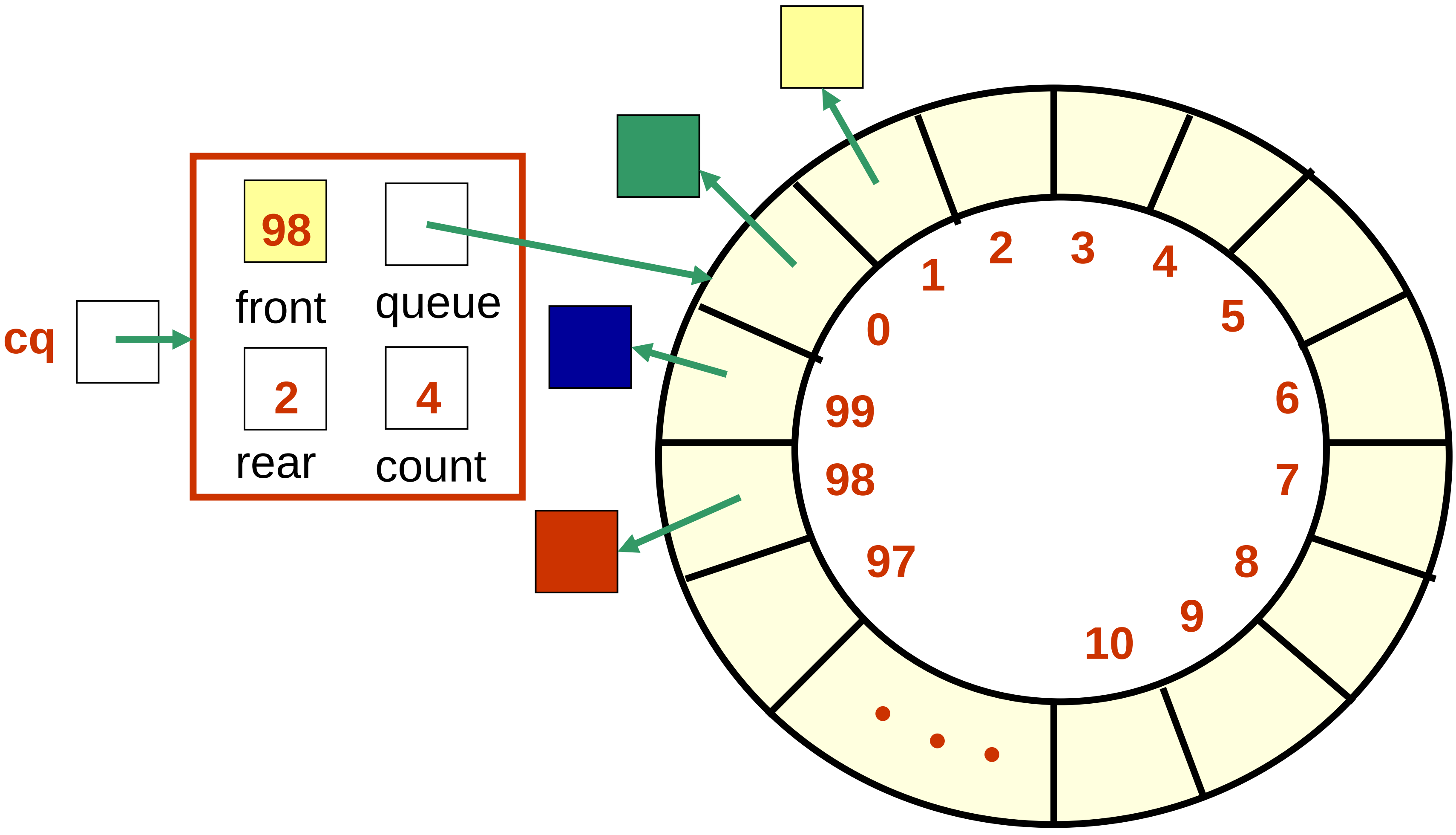
Second Approach: Queue as a Circular Array

- If we do not fix one end of the queue at index 0, we will not have to shift elements
- ***Circular array*** is an array that conceptually loops around on itself
  - The last index is thought to "***precede***" index 0
  - In an array whose last index is **n**, the location "***before***" index **0** is index **n**; the location "***after***" index **n** is index **0**
- We need to keep track of where the ***front*** as well as the ***rear*** of the queue are at any given time

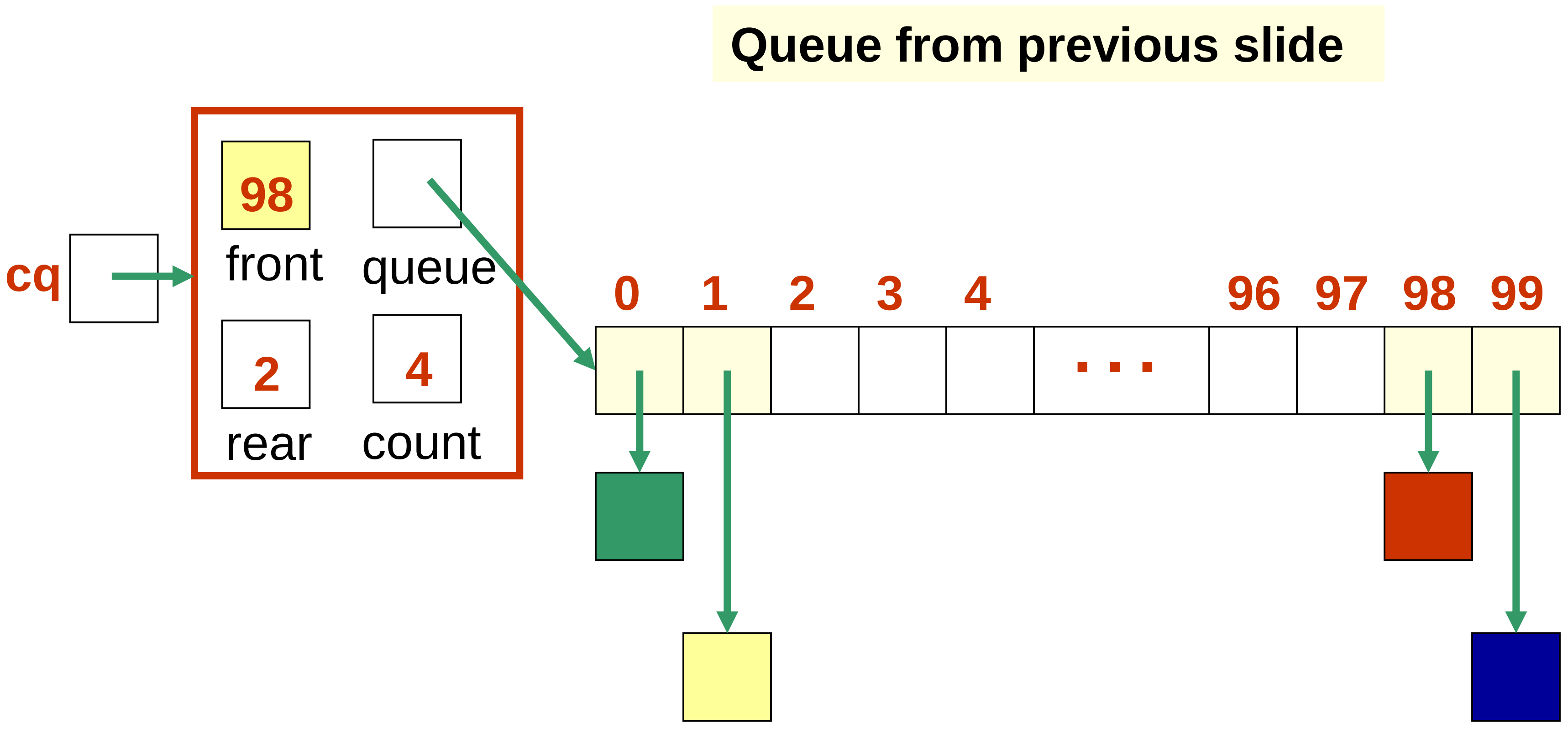
Circular Array Implementation of a Queue



A Queue Straddling the End of a Circular Array



Circular Queue Drawn Linearly



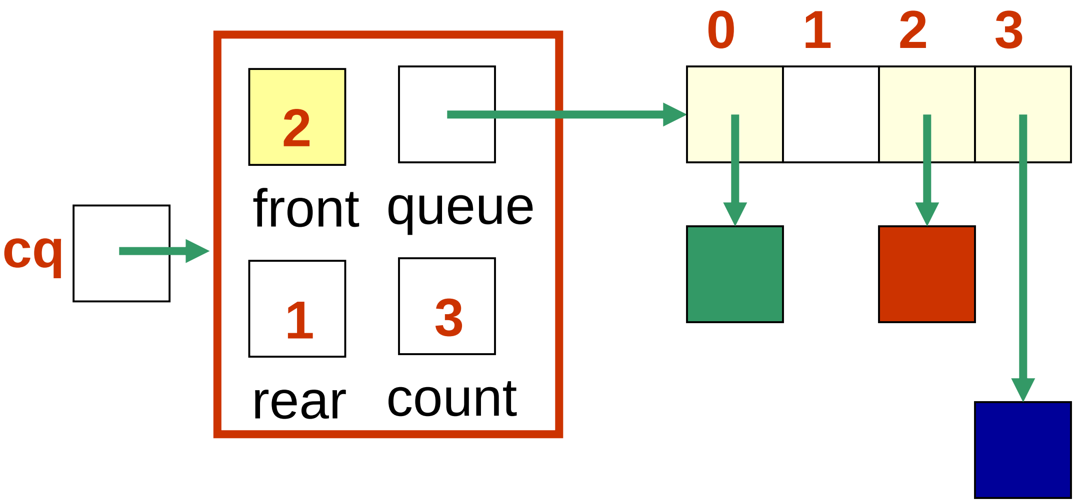
Circular Array Implementation

- When an element is enqueued, the value of **rear** is incremented
- But it must take into account the need to loop back to index 0:

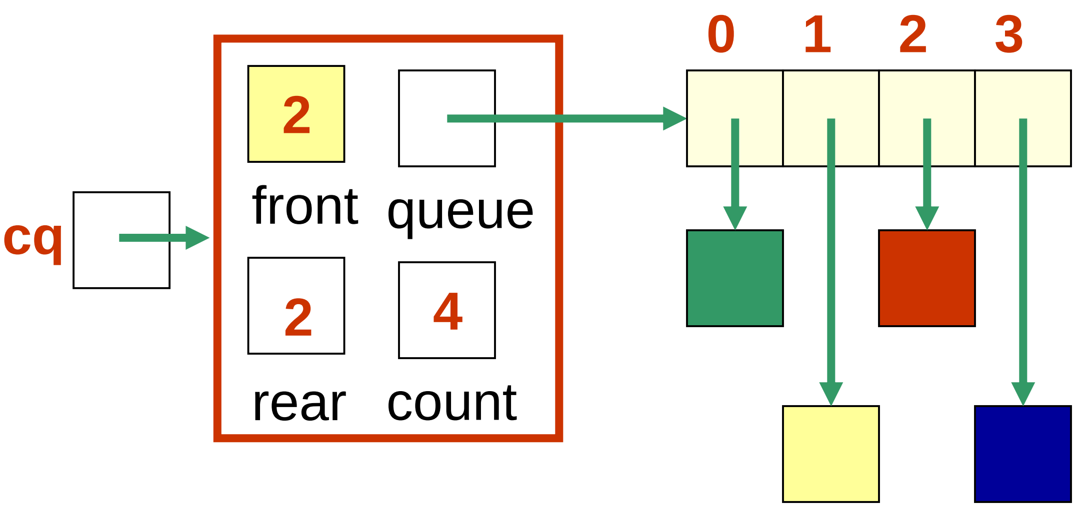
rear = (rear+1) % queue.length;

- Can this array implementation also reach capacity?

Example: array of length 4
What happens?

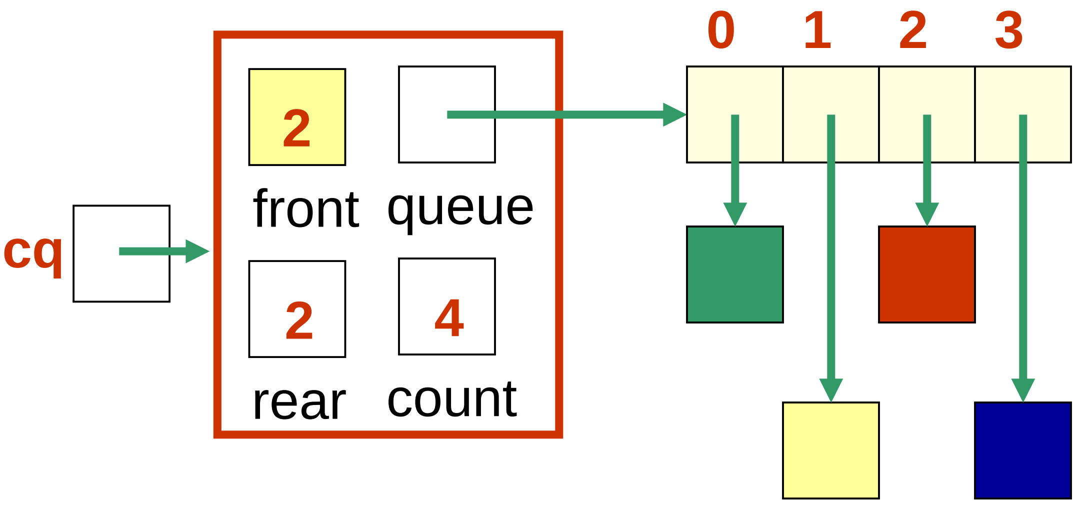


Suppose we try to add one more item to a queue implemented by an array of length 4

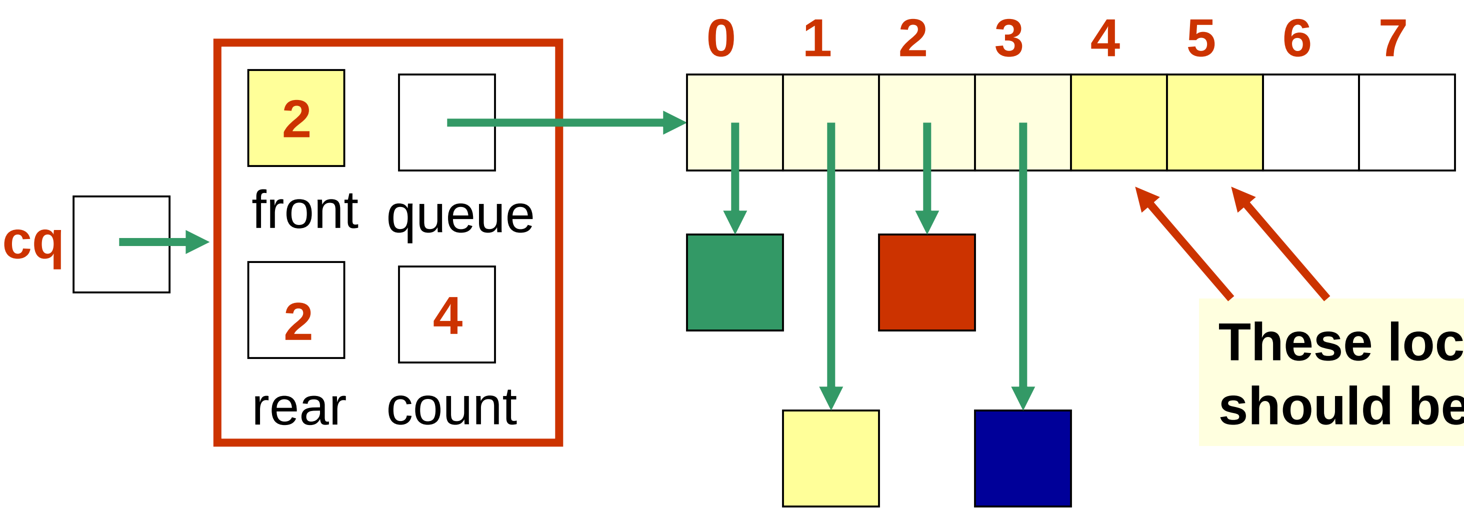


The queue is now full. How can you tell?

Add another item!
Need to expand capacity…

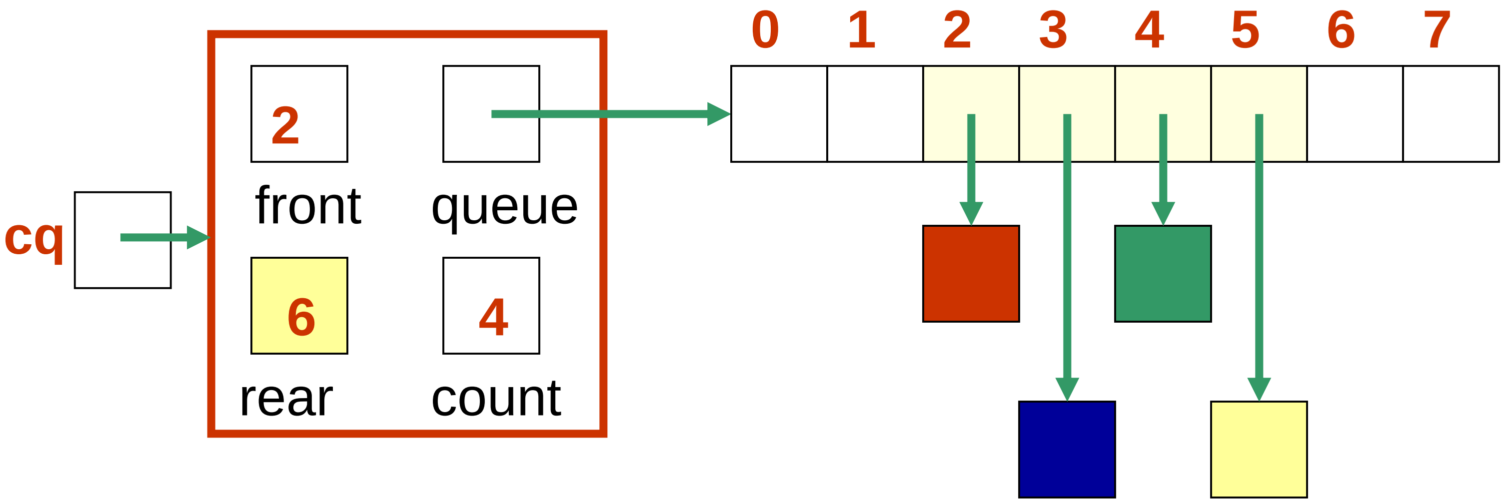


We can't just double the size of the array and copy values to the same positions as before: circular properties of the queue will be lost

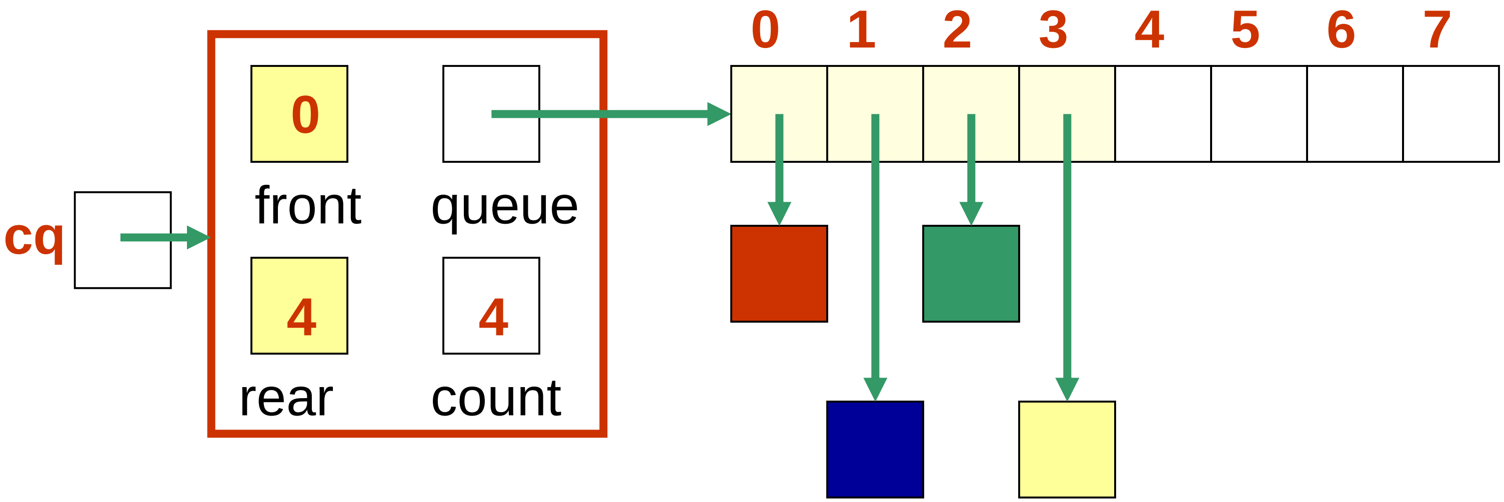


These locations should be in use

We *could* build the new array, and copy the queue elements into contiguous locations beginning at location front:

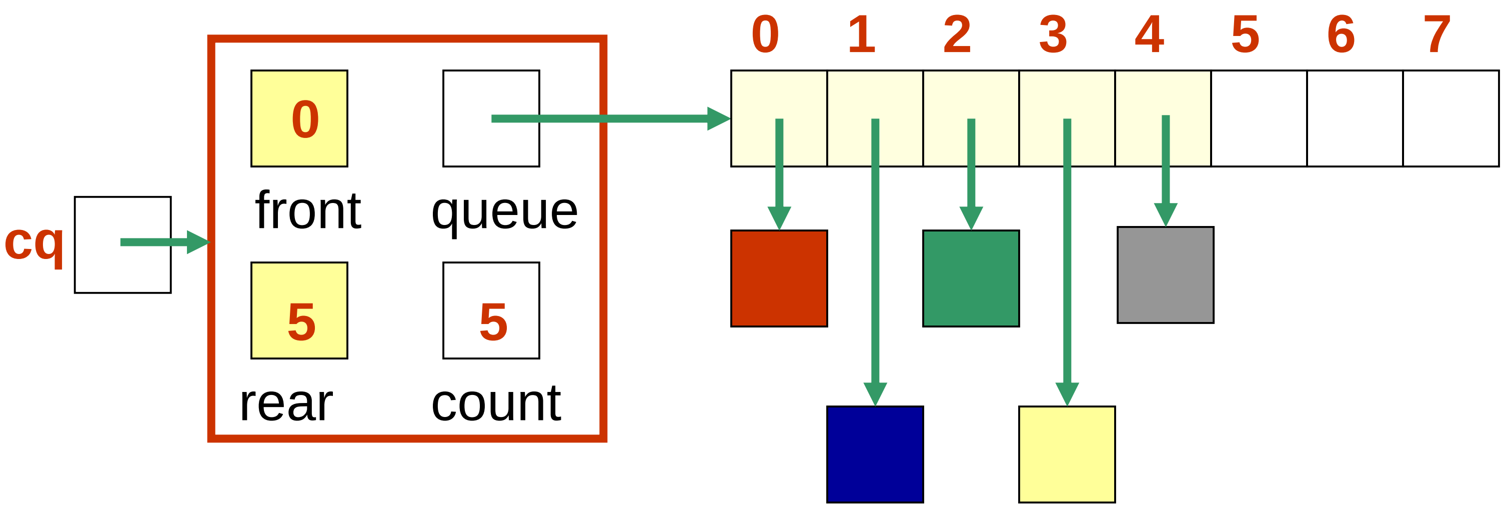


Or, we could copy the queue elements in order to the *beginning* of the new array



New element is added at rear = (rear+1) % queue.length

See *expandCapacity()* in *CircularArrayQueue.java*



Pseudocode for the Enqueue Operation Using a Circular Array Implementation of a Queue

```
Algorithm enqueue(element)
   if queue is full then expandQueue()
   rear = (rear + 1) mod size of queue
   queue[rear] = element
   ++count

Algorithm expandQueue()
      q  = new array of size 2 * size of queue
      copied = 0  // number of elements copied to the larger array
      i = 0       // index of next entry in array q
      j = front  // index of next entry in array queue
      while copied < count do { // copy data to new array
         q[i] = queue[j]
         ++i
         j = (j + 1) mod size of queue
         ++ copied
      }
      rear = count – 1  // position of last element in the queue
      front = 0
      queue = q
```

Enqueue Operation in Java

```
public void enqueue (T element) {
        if (count == queue.length) expandQueue();
        rear = (rear + 1) % queue.length;
        queue[rear] = element;
        ++count;
}
```

Enqueue Operation in Java

```
public void expandQueue() {
        T[] q = (T[]) new Object[2*queue.length];
        copied = 0; // number of data items copied to larger array
        i = 0;    // index of next entry in array q
        j = front; // index of next entry in array queue
        while (copied < count) {
                q[i] = queue[j];
                ++i;
                j = (j + 1) % queue.lengtht;
                ++copied;
        }
        rear = count – 1;
        front = 0;
        queue = q
}
```

Algorithm in Pseudocode for the Dequeue Operation Using a Circular Array Representation of a Queue

```
Algorithm dequeue() {
        if queue is empty then ERROR
        result = queue[front]
        count = count – 1
        front = (front + 1) mod (size of array queue)
        return result
}
```

Where **mod** is the modulo operator (or modulus or remainder), denoted % in Java.

Dequeue Operation in Java

```
public T dequeue() {
        if (isEmpty())
                throw new EmptyQueueException();
        result = queue[front];
        count = count -1;
        front = (front + 1) % queue.length;
        return result;
}
```