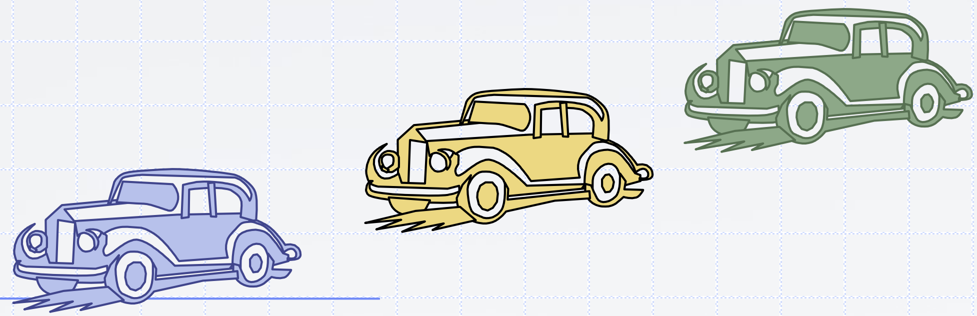
Queues



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These slides have been extracted, modified and updated from original slides of :
Data Structures and Algorithms in Java, 5th edition. John Wiley& Sons, 2010. ISBN 978-0-470-38326-1.
Data Structures and the Java Collections Framework by William J. Collins, 3rdedition, ISBN 978-0-470-48267-4.
Both books are published by Wiley.

The Queue ADT

- The Queue ADT stores arbitrary objects.
- Insertions and deletions follow the first-in first-out (FIFO) scheme.
- Insertions are at the rear of the queue and removals are at the front of the queue.
- Main queue operations:
  - enqueue(object): inserts an element at the end of the queue
  - object dequeue(): removes and returns the element at the front of the queue

The Queue ADT

- Auxiliary queue operations:
  - object front(): returns the element at the front without removing it.
  - integer size(): returns the number of elements stored.
  - boolean isEmpty(): indicates whether no elements are stored.
- Exceptions
  - Attempting the execution of dequeue or front on an empty queue throws an EmptyQueueException

Example

Operation	*Output*	*Q Contents*
enqueue(5)	--	[5]
enqueue(3)	--	[5, 3]
dequeue()	5	[3]
enqueue(7)	--	[3, 7]
dequeue()	3	[7]
front()	7	[7]
dequeue()	7	[]
dequeue()	*"error"*	[]
enqueue(9)	--	[9]
isEmpty()	*false*	[9]
size()	1	[9]
dequeue()	9	[]

Applications of Queues

- Direct applications
  - Waiting lists, bureaucracy
  - Access to shared resources (e.g., printer)
  - Multiprogramming
- Indirect applications
  - Auxiliary data structure for algorithms
  - Component of other data structures

Array-based Queue

- Can be implemented using an array, Q, of fixed capacity.
- Use an array of size N in a circular fashion.
- We can let $Q[0]$ be the front of the queue, however this is inefficient since each dequeue() operation would result in moving all remaining elements forward.
- That is, each dequeue() operation would have a complexity of $O(n)$.

Array-based Queue

- Instead, two variables keep track of the front and rear:
  - f index of the front element
  - r index of the next available element in the array (that is the one immediately past the rear/last element)
- Initially, we assign $f = r = 0$, which indicates that the queue is empty (generally $f = r$ indicates empty queue).
- Index r is kept empty. Insertion is made into $Q[r]$ then r is incremented.

Array-based Queue

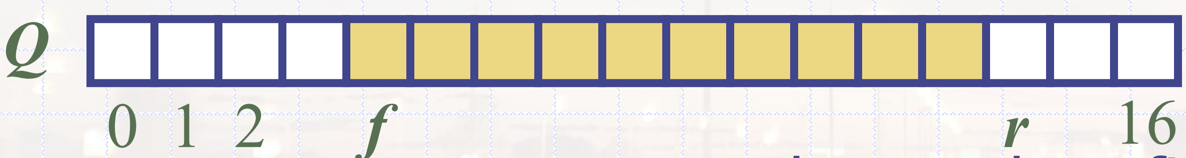
- This configuration would allow enqueue(), dequeue() and front() to be performed in constant time, that is $O(1)$.
- However, this configuration has a serious problem.
- For example, if we repeatedly enqueue and dequeue a single element *N* times, then we end up with assign $f = r =$ N (indicating an empty queue, which is correct). Below is another example.

- While the array clearly has many empty elements, an insertion cannot be made as it would result in array-out-of-bounds error.

Array-based Queue

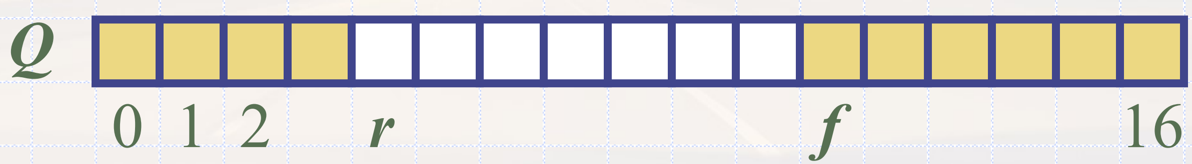
- Instead of having this normal configuration, we can let the indices *f* and *r* wrap around the end of the array.
- That is view the array as a "circular array" that goes from *Q*[*0*] to *Q*[*N - 1*] then back to *Q*[*0*].
- Notice that Index *r* is kept empty, which means that the queue can hold a maximum of N-1 elements.

normal configuration



- For example, N=17, queue can hold a maximum of 16 elements.

wrapped-around configuration

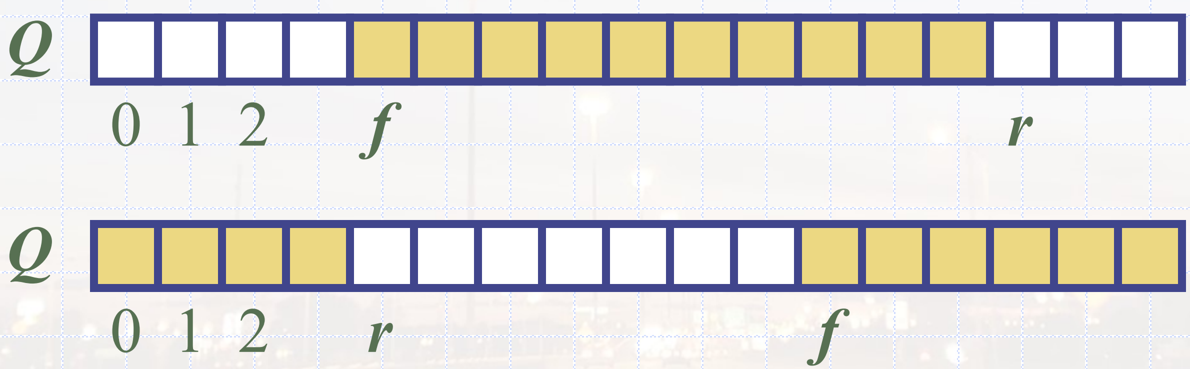


Queue Operations

- We use the modulo operator (remainder of division)

Algorithm *size*()
  return $((N - f) + r) \bmod N$

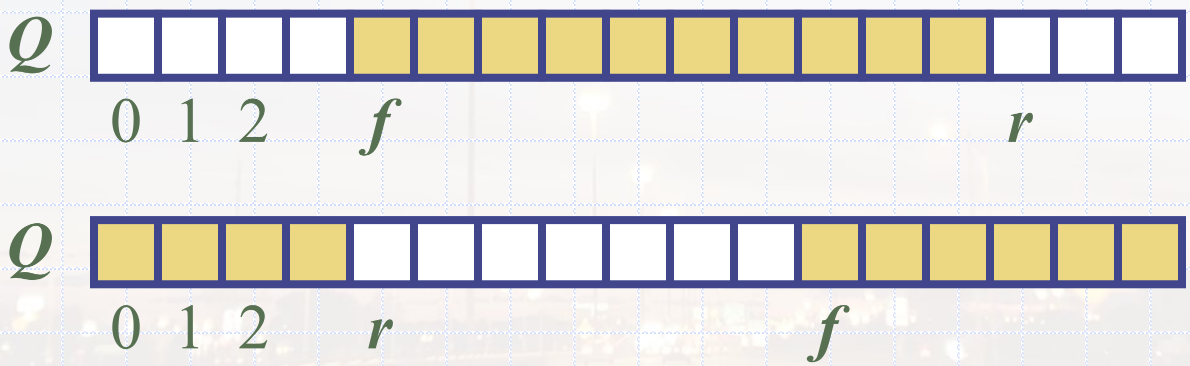
Algorithm *isEmpty*()
  return $(f = r)$



Queue Operations (cont.)

- Operation enqueue throws an exception if the array is full
- This exception is implementation-dependent

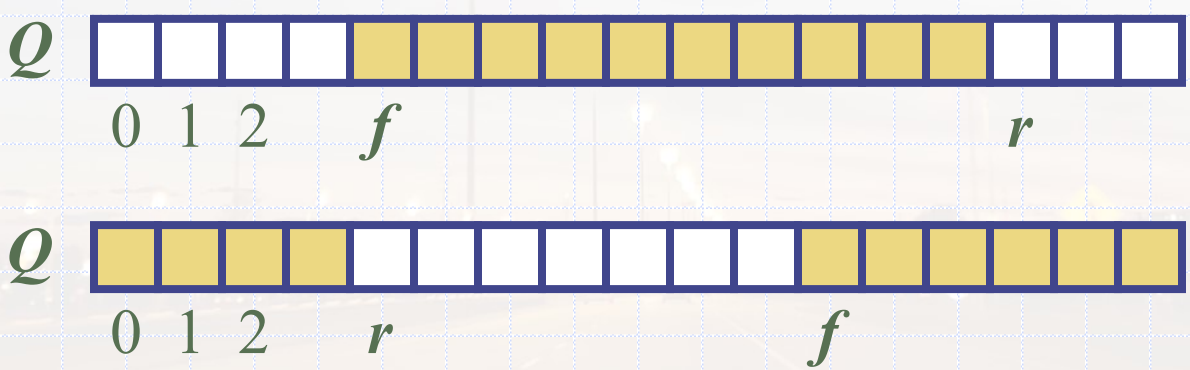
Algorithm *enqueue*(o)
  if $size() = N - 1$ **then**
    throw *FullQueueException*
  else
    $Q[r] \leftarrow o$
    $r \leftarrow (r + 1) \bmod N$



Queue Operations (cont.)

- Operation dequeue throws an exception if the queue is empty
- This exception is specified in the queue ADT

Algorithm *dequeue*()
  if *isEmpty*() **then**
    throw *EmptyQueueException*
  else
    $o \leftarrow Q[f]$
    $f \leftarrow (f + 1) \bmod N$
    return *o*



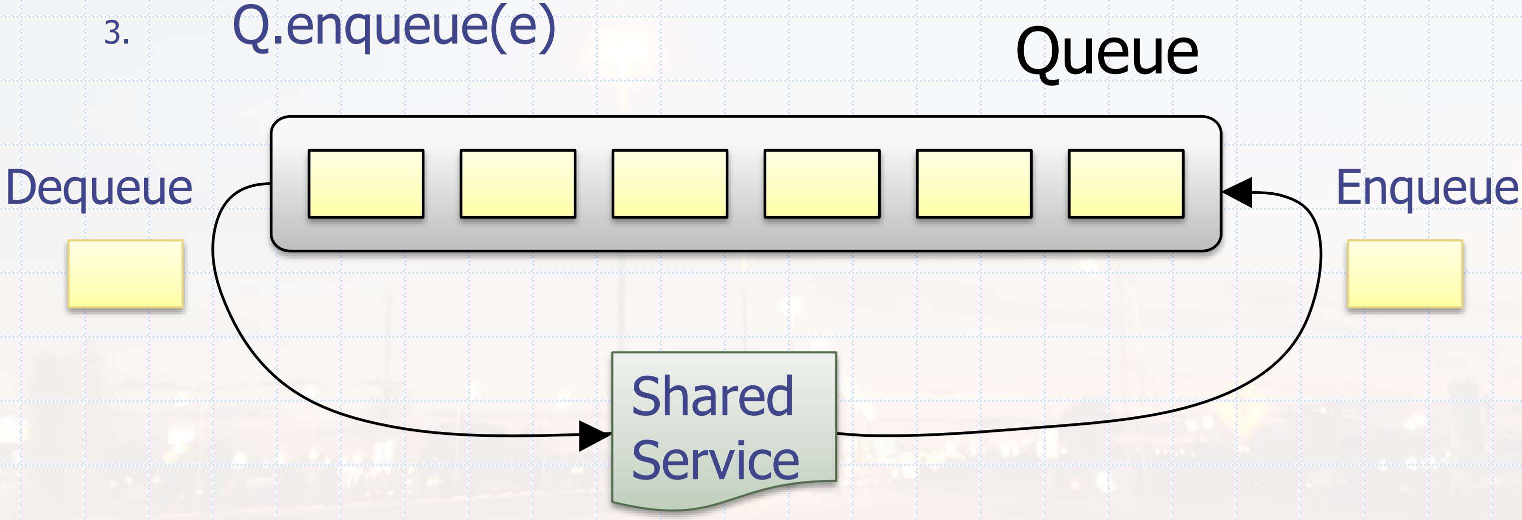
Queue Interface

- Java interface corresponding to our Queue ADT
(Note: not identical to the shown interface)
- Requires the definition of class EmptyQueueException
- There is no corresponding built-in Java class

```
public interface Queue<E> {
   public int size();
   public boolean isEmpty();
   public E front()
         throws EmptyQueueException;
   public void enqueue(E element);
   public E dequeue()
         throws EmptyQueueException;
}
```

Application: Round Robin Schedulers

- We can implement a round robin scheduler using a queue Q by repeatedly performing the following steps:
  1. e = Q.dequeue()
  2. Service element e
  3. Q.enqueue(e)



Growable Array-based Queue

- In an enqueue() operation, when the array is full, we can replace the array with a larger one instead of throwing an exception.

- Similar to what have been explained for growable array-based stack, the enqueue() operation has amortized running time of:
  - *O(n) with the incremental strategy*
  - *O(1) with the doubling strategy*

Double-Ended Queues

- A *double-ended queue* (dequeue, or D.Q.) ADT is richer than the stack ADT and the queue ADT.
- It supports insertion and deletion at both ends.
- Elements can only be added to or removed from the front (head) or the back (tail).

Double-Ended Queues

- The fundamentals operations allowed by such queue are:
  - addFirst(*e*): Insert as new element at the head of the queue.
  - addLast(*e*): Insert as new element at the tail of the queue.
  - removeFirst(): Remove and return the first element of the D.Q., or an error if the queue is empty.
  - removeLast(): Remove and return the last element of the D.Q., or an error if the queue is empty.
- Other operations may include: getFirst(), getLast(), size() and isEmpty()

Example

Operation	*Output*	*D.Q. Contents*
addFirst(3)	--	[3]
addFirst(5)	--	[5, 3]
removeFirst()	5	[3]
addLast(7)	--	[3, 7]
addLast(9)	--	[3, 7,9]
addLast(12)	--	[3, 7,9, 12]
addFirst(8)	--	[8,3, 7,9, 12]
removeLast()	12	[8,3, 7,9]
removeFirst()	8	[3, 7,9]
isEmpty()	*false*	[3, 7,9]
addFirst(6)	--	[6, 3, 7,9]
size()	4	[6, 3, 7,9]