Lecture 3
Linear Data Structures
Learning Outcomes

• Based on this lecture, you should:
  – Know the basic linear data structures
  – Be able to express each as an Abstract Data Type (ADT)
  – Be able to specify each of these ADTs as a Java interface.
  – Be able to outline the algorithms for creating, accessing and modifying each data structure
  – Be able to analyze the running time of these operations
  – Be able to identify particular applications for which each data structure would be suited.
Linear Data Structures

- Arrays (Ch. 3.1)
- Array Lists (Ch. 7.2)
- Stacks (Ch. 6.1)
- Queues (Ch. 6.2)
- Linked Lists (Ch. 3.2 – 3.4)
Linear Data Structures

• Arrays (Ch. 3.1)
• Array Lists (Ch. 7.2)
• Stacks (Ch. 6.1)
• Queues (Ch. 6.2)
• Linked Lists (Ch. 3.2 – 3.4)
Arrays

- Array: a sequence of indexed components with the following properties:
  - **array size is fixed** at the time of array’s construction
    - `int[] numbers = new int [10];`
  - **array elements are placed contiguously** in memory
    - address of any element can be calculated directly as its offset from the beginning of the array
  - consequently, array components **can be efficiently inspected or updated** in O(1) time, using their indices
    - `randomNumber = numbers[5];`
    - `numbers[2] = 100;`
Arrays in Java

• For an array of length $n$, the index bounds are 0 to $n-1$.
• Java arrays are homogeneous
  – all array components must be of the same (object or primitive) type.
  – but, an array of an object type can contain objects of any respective subtype
• An array is itself an object.
  – it is allocated dynamically by means of `new`
  – it is automatically deallocated when no longer referred to
• When an array is first created, all values are automatically initialized with
  – 0, for an array of int[] or double[] type
  – false, for a boolean[] array
  – null, for an array of objects
• Example [ common error –unallocated arrays]
  ```java
  int[] numbers;
  numbers[2] = 100;
  ```
Arrays in Java

• The length of any array object can be accessed through its instance variable `length`.
  – the cells of an array A are numbered: 0, 1, .., A.length-1

• ArrayIndexOutOfBoundsException
  – thrown at an attempt to index into array A using a number larger than A.length-1.
  – helps Java avoid ‘buffer overflow attacks’

• Example [ declaring, defining and determining the size of an array]

  ```java
  int[] A={12, 24, 37, 53, 67};
  for (int i=0; i < A.length; i++) {
    ...
  }
  ```
Buffer Overflows

Windows Buffer Overflow Protection Programs: Not Much

<"Paul Robinson" <postmaster@paul.washington.dc.us>>

Tue, 10 Aug 2004 15:26:44 GMT An 9 Aug 2004

…there is a bug in AOL Instant Messenger allowing an attacker to send a message that can cause a buffer overflow and possibly execute code on the attacked machine. Apparently this will only occur if the attacker sends a url - like the one in this message - as a hyperlink and the victim clicks on it, which makes the probability of attack much lower than a "standard buffer overflow attack" upon a program.

Mon, 09 Aug 2004 17:24:19 GMT

…a buffer overflow exploit is one in which someone sends too much data to a program (such as a web server application), sending far more data than the program would expect, in order to force arbitrary data into a storage area (a "buffer") so the amount of data forced into the buffer goes beyond the expected limits, causing the data to overflow the buffer and makes it possible for that data to be executed as arbitrary program code. Since the attacker forces code of his choosing into the execution stream, he now owns your box, because as the saying goes, if I can run code on your machine - especially if it's a Windows machine where there is not much protection - I can pretty much do anything I please there.
Arrays in Java

- Since an array is an object, the name of the array is actually a **reference** (pointer) to the place in memory where the array is stored.
  - Reference to an object holds the **address** of the actual object

- Example [copying array references]
  ```java
  int[] A={12, 24, 37, 53, 67};
  int[] B=A;
  B[3]=5;
  ```

- Example [cloning an array]
  ```java
  int[] A={12, 24, 37, 53, 67};
  int[] B=A.clone();
  B[3]=5;
  ```
Example

Examples [2D array in Java = array of arrays]

• int[][] nums = new int[5][4];

OR

• int[][] nums;
  
  nums = new int[5][];
  
  for (int i=0; i<5; i++) {
    
      nums[i] = new int[4];
  
  }
Caution

- Clone does a **shallow** copy

```java
int[][] A = new int[5][4];
...
int[][] B = A.clone();
```
Caution

• This is also affects cloning of one-dimensional arrays of reference types (objects).

• Example: Person[] guests = contacts.clone();

![Diagram showing cloning of one-dimensional arrays of reference types](diagram.png)
Deep Copies

• Deep copies must be made by iteratively cloning or copying individual elements.

• Example:

```java
Person[] guests = new Person[contacts.length];
for (int k=0; k < contacts.length; k++)
    guests[k] = (Person) contacts[k].clone();
```
Assignment 1, Question 2

• In image processing, a frequent operation is to compute the average image value (intensity) or some other statistic over a rectangular sub-region of the image. The region of interest can be specified by 4 integer parameters: top, bottom, left and right.

• We will implement a class called \texttt{IntegralImage}, which will allow the average over an arbitrary rectangular sub-image to be computed in $O(1)$ time, using only $O(n)$ memory.

• Images will be stored in 2D arrays. The first index of the array indicates the row number (vertical position) and the second index indicates the column number (horizontal position). Vertical position is indexed from the top down, and horizontal position is indexed from left to right. Thus image[0][0] is the top left pixel of the image.

• The constructor method \texttt{IntegralImage} will accept an input integer image and \textbf{will construct, in $O(n)$ time, a new data structure} using $O(n)$ memory \textbf{that will allow $O(1)$ computation of sub-image averages}. If the input array is not rectangular, \texttt{IntegralImage} will throw an \texttt{InvalidImageException}.

• The query method \texttt{meanSubImage(top, bottom, left, right)} will return the average of all pixels in the subimage extending from top to bottom bounds vertically and left to right bounds horizontally, in $O(1)$ time. The pixels lying at the bounds are included in this calculation.
Sept 22, 2015

End of Lecture
The **Java.util.Arrays** Class

- **Useful Built-In Methods in** *Java.util.Arrays*
  - `equals(A,B)`
    - returns true if A and B have an equal number of elements and every corresponding pair of elements in the two arrays are equal
  - `fill(A,x)`
    - store element x into every cell of array A
  - `sort(A)`
    - sort the array A in the natural ordering of its elements
  - `binarySearch([int] A, int key)`
    - search the specified array of sorted ints for the specified value using the binary search algorithm (A must be sorted)
What is Printed?

```java
import java.util.Arrays;

int[] A={12, 24, 37, 53, 67};
int[] B=A.clone();

if (A==B) {
    System.out.println(" Superman ");
}

if (Arrays.equals(A, B)) {
    System.out.println(" Snow White ");
}

Answer: Snow White
```
Caution

- As for clone, Arrays.equals(a,b) tests for **shallow** equality

What is printed?

```java
int[][] B = A.clone();

if (Arrays.equals(A, B)) {
    System.out.println(" Snow White ");
} else {
    System.out.println(" Superman ");
}
```

**Answer: Superman**
Limitations of Arrays

• Static data structure
  – size must be fixed at the time the program creates the array
  – once set, array size cannot be changed
  – if number of entered items > declared array size ⇒ out of memory
    • fix 1: use array size > number of expected items ⇒ waste of memory
    • fix 2: increase array size to fit the number of items ⇒ extra time

• Insertion / deletion in an array is time consuming
  – all the elements following the inserted element must be shifted appropriately

• Example [ time complexity of “growing” an array]
  if (numberOfItems > numbers.length) {
    int[] newNumbers = new int[2*numbers.length];
    System.arraycopy(numbers, 0, newNumbers, 0, numbers.length);
    numbers = newNumbers; // Source start idx Dest start idx
  }
Linear Data Structures

- Arrays (Ch. 3.1)
- **Array Lists (Ch. 7.2)**
- Stacks (Ch. 6.1)
- Queues (Ch. 6.2)
- Linked Lists (Ch. 3.2 – 3.4)
The Array List ADT

- Like an array, the Array List ADT stores a sequence of arbitrary objects.

- An element can be accessed, modified, inserted or removed by specifying its rank (number of elements preceding it).

- An exception is thrown if an incorrect rank is specified (e.g., a negative rank).
The Array List ADT

/** Simplified version of java.util.List */
public interface List<E> {

/** Returns the number of elements in this list */
public int size();

/** Returns whether the list is empty. */
public boolean isEmpty();

/** Append element e to end of list */
public void add(E e);

/** Inserts an element e to be at index I, shifting all elements after this right. */
public void add(int I, E e) throws IndexOutOfBoundsException;

/** Returns the element at index I, without removing it. */
public E get(int i) throws IndexOutOfBoundsException;

/** Removes and returns the element at index I, shifting the elements after this left. */
public E remove(int i) throws IndexOutOfBoundsException;

/** Replaces the element at index I with e, returning the previous element at i. */
public E set(int I, E e) throws IndexOutOfBounds

A Simple Array-based Implementation

- Use an array $V$ of size $N$
- A variable $n$ keeps track of the size of the array list (number of elements stored)
- Operation $\text{get}(r)$ is implemented in $O(1)$ time by returning $V[r]$
Insertion

- In operation $\text{add}(r, e)$, we need to make room for the new element by shifting forward the $n - r$ elements $V[r], \ldots, V[n - 1]$
- In the worst case ($r = 0$), this takes $O(n)$ time
Deletion

• In operation \texttt{remove}(r), we need to fill the hole left by the removed element by shifting backward the \( n - r - 1 \) elements \( V[r+1], \ldots, V[n-1] \)

• In the worst case \( (r = 0) \), this takes \( O(n) \) time

\begin{itemize}
  \item \begin{array}{c}
  V \\
  0 \ 1 \ 2 \ \ \ \ \ r \ \ \ \ \ n \\
  \end{array}
  \begin{array}{c}
  V \\
  e \\
  \end{array}
  \begin{array}{c}
  V \\
  0 \ 1 \ 2 \ \ \ \ \ r \ \ \ \ \ n \\
  \end{array}
  \begin{array}{c}
  V \\
  \end{array}
\end{itemize}
Performance

• In the array based implementation
  – The space used by the data structure is $O(n)$
  – `size`, `isEmpty`, `get` and `set` run in $O(1)$ time
  – `add` and `remove` run in $O(n)$ time

• In an `add` operation, when the array is full, instead of throwing an exception, we could replace the array with a larger one.

• In fact `java.util.ArrayList` implements this ADT using extendable arrays that do just this.
Implementing Array Lists using Extendable Arrays

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

- How large should the new array be?
  - incremental strategy: increase the size by a constant $c$
  - doubling strategy: double the size

- Let
  - $n =$ current number of elements in array
  - $N =$ capacity of array

**Algorithm** $add(e)$

```plaintext
if $n = N$
    then
        $A \leftarrow$ new array of size $N^*$
        $N = N^*$
        for $i \leftarrow 0$ to $N-1$ do
            $A[i] \leftarrow S[i]$
        $S \leftarrow A$
        $n \leftarrow n + 1$
        $S[n] \leftarrow e$
```
Comparison of the Strategies

• We compare the incremental strategy and the doubling strategy by analyzing the total time $T(n)$ needed to perform a series of $n$ add operations.

• We simplify the analysis by assuming add(e) operations that append the object to the end of the list.

• We assume that we start with an empty array list ($n = 0$) represented by an array of capacity 0 ($N = 0$).

• The amortized time of an add(e) operation is the average time taken over the series of operations, i.e., $T(n)/n$. 
### Incremental Strategy

<table>
<thead>
<tr>
<th>$n$</th>
<th>$N$</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>$c$</td>
<td>Extend array</td>
</tr>
<tr>
<td>2</td>
<td>$c$</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$c$</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$2c$</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$3c$</td>
<td>Extend array</td>
</tr>
<tr>
<td></td>
<td>$kc$, where $k = \left\lfloor \frac{n}{c} \right\rfloor$</td>
<td></td>
</tr>
</tbody>
</table>
Incremental Strategy Analysis

• We replace the array \( k = \left\lfloor \frac{n}{c} \right\rfloor \) times

• The total time \( T(n) \) of a series of \( n \text{ add(e)} \) operations is proportional to

\[
\begin{align*}
&n + c + 2c + 3c + 4c + \ldots + kc = \\
&n + c(1 + 2 + 3 + \ldots + k) = \\
&n + ck(k + 1)/2
\end{align*}
\]

• (Recall that JAVA initializes all elements of an allocated array.)

• Since \( c \) is a constant, \( T(n) \) is \( O(n + k^2) \), i.e., \( O(n^2) \)

• The amortized time of an \( \text{add(e)} \) operation is \( O(n) \)
Doubling Strategy Analysis

- We replace the array \( k = \lceil \log n \rceil + 1 \) times
- The total time \( T(n) \) of a series of \( n \) \textit{add(o)} operations is proportional to
  \[
  n + 1 + 2 + 4 + 8 + \ldots + 2^k
  \]
  \[
  = n + 2^{k+1} - 1
  \]
  \[
  \leq 9n
  \]
- Thus \( T(n) \) is \( O(n) \)
- The amortized time of an add operation is \( O(1) \)!

\[
\left(\text{Recall: } \sum_{i=0}^{n} r^i = \frac{1 - r^{n+1}}{1 - r}\right)
\]
Applications of Array Lists

• Maintaining a sorted list when insertions and removals are relatively rare.
  – List of plant species by name
  – List of elements by atomic weight
## Doubling Strategy

<table>
<thead>
<tr>
<th>n</th>
<th>N</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>1</td>
<td>Extend array</td>
</tr>
<tr>
<td>2</td>
<td>2</td>
<td>Extend array</td>
</tr>
<tr>
<td>3</td>
<td>4</td>
<td>Extend array</td>
</tr>
<tr>
<td>4</td>
<td>4</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>8</td>
<td>Extend array</td>
</tr>
<tr>
<td>6</td>
<td>8</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>8</td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>8</td>
<td></td>
</tr>
<tr>
<td></td>
<td>:</td>
<td></td>
</tr>
<tr>
<td>n</td>
<td>(2^k), where (k = \lfloor \log n \rfloor)</td>
<td></td>
</tr>
</tbody>
</table>
Sept 24, 2015

End of Lecture
Linear Data Structures

- Arrays (Ch. 3.1)
- Array Lists (Ch. 7.2)
- Stacks (Ch. 6.1)
- Queues (Ch. 6.2)
- Linked Lists (Ch. 3.2 – 3.4)
The Stack ADT

- The Stack ADT stores arbitrary objects.
- Insertions and deletions follow the last-in first-out scheme.
- Think of a spring-loaded plate or Pez dispenser.
- Main stack operations:
  - `push(e)`: inserts an element
  - `object pop()`: removes and returns the last inserted element
- Auxiliary stack operations:
  - `object top()`: returns the last inserted element without removing it
  - `integer size()`: returns the number of elements stored
  - `boolean isEmpty()`: indicates whether no elements are stored

Note: `java.util.Stack` provides push and pop, but differs in other respects.
Stack Interface

- Assumes null is returned from top() and pop() when stack is empty
- Different from the built-in Java class java.util.Stack

```java
public interface Stack<E> {
    int size();
    boolean isEmpty();
    E top();
    void push(E element);
    E pop();
}
```
## Example

<table>
<thead>
<tr>
<th>Method</th>
<th>Return Value</th>
<th>Stack Contents</th>
</tr>
</thead>
<tbody>
<tr>
<td>push(5)</td>
<td>–</td>
<td>(5)</td>
</tr>
<tr>
<td>push(3)</td>
<td>–</td>
<td>(5, 3)</td>
</tr>
<tr>
<td>size()</td>
<td>2</td>
<td>(5, 3)</td>
</tr>
<tr>
<td>pop()</td>
<td>3</td>
<td>(5)</td>
</tr>
<tr>
<td>isEmpty()</td>
<td>false</td>
<td>(5)</td>
</tr>
<tr>
<td>pop()</td>
<td>5</td>
<td>()</td>
</tr>
<tr>
<td>isEmpty()</td>
<td>true</td>
<td>()</td>
</tr>
<tr>
<td>pop()</td>
<td>null</td>
<td>()</td>
</tr>
<tr>
<td>push(7)</td>
<td>–</td>
<td>(7)</td>
</tr>
<tr>
<td>push(9)</td>
<td>–</td>
<td>(7, 9)</td>
</tr>
<tr>
<td>top()</td>
<td>9</td>
<td>(7, 9)</td>
</tr>
<tr>
<td>push(4)</td>
<td>–</td>
<td>(7, 9, 4)</td>
</tr>
<tr>
<td>size()</td>
<td>3</td>
<td>(7, 9, 4)</td>
</tr>
<tr>
<td>pop()</td>
<td>4</td>
<td>(7, 9)</td>
</tr>
<tr>
<td>push(6)</td>
<td>–</td>
<td>(7, 9, 6)</td>
</tr>
<tr>
<td>push(8)</td>
<td>–</td>
<td>(7, 9, 6, 8)</td>
</tr>
<tr>
<td>pop()</td>
<td>8</td>
<td>(7, 9, 6)</td>
</tr>
</tbody>
</table>
Applications of Stacks

- Page-visited history in a Web browser
- Undo sequence in a text editor
- Chain of method calls in the Java Virtual Machine
- Parsing math
Method Stack in the JVM

- The Java Virtual Machine (JVM) keeps track of the chain of active methods with a stack

- When a method is called, the JVM pushes on the stack a frame containing
  - Local variables
  - Program counter, keeping track of the statement being executed

- When a method ends, its frame is popped from the stack and control is passed to the method on top of the stack

- Allows for recursion

```java
main() {
    int i = 5;
    foo(i);
}

foo(int j) {
    int k;
    k = j+1;
    bar(k);
}

bar(int m) {
    ...
}
```
Array-based Stack

- The Stack ADT can be implemented with an array
- We add elements from left to right
- A variable keeps track of the index of the top element

Algorithm `size()`

```plaintext
return t + 1
```

Algorithm `pop()`

```plaintext
if `isEmpty()` then
    return null
else
    t ← t - 1
    return S[t + 1]
```

```plaintext
S
0 1 2 ...
```
Array-based Stack (cont.)

- If using an array of fixed size, the stack may become full
- A push operation will then throw an `IllegalStateException`
  - Limitation of the array-based implementation
  - Not intrinsic to the Stack ADT
  - For example, in `java.util.Stack`, the array is extendable.

```
Algorithm push(e)
    if t = S.length - 1 then
        throw IllegalStateException
    else
        t ← t + 1
        S[t] ← e
```

```text
S
0 1 2 ...
```

```text
Last Updated: September 29, 2015
```
Performance and Limitations

• Performance
  – Let $n$ be the number of elements in the stack
  – The space used is $O(n)$
  – Each operation runs in time $O(1)$
Array-based Stack in Java

```java
public class ArrayStack<E> implements Stack<E> {
    // holds the stack elements
    private E[] S;
    // index to top element
    private int top = -1;
    // constructor
    public ArrayStack(int capacity) {
        S = (E[]) new Object[capacity];
    }

    public E pop() {
        if (isEmpty())
            return null;
        E temp = S[top];
        // facilitate garbage collection:
        S[top] = null;
        top = top - 1;
        return temp;
    }

    ... (other methods of Stack interface)
```
Example Use in Java

```java
public class Tester {
    // … other methods
    public intReverse(Integer a[]) {
        Stack<Integer> s;
        s = new ArrayStack<Integer>();
        s = new ArrayStack<Integer>();
        … (code to reverse array a) …
    }

    public floatReverse(Float f[]) {
        Stack<Float> s;
        s = new ArrayStack<Float>();
        … (code to reverse array f) …
    }
}
```
Example Application: Parenthesis Matching

• Each “(”, “{”, or “[” must be paired with a matching “)””, “}”, or “[”
  – correct: ( )(( )){([ )])}
  – correct: ((( )(( )){([ )])}
  – incorrect: )(( )){([ )])}
  – incorrect: {[ ]})
  – incorrect: (  

• Note that each closing symbol must match the most recent unmatched open symbol.
 Parentheses Matching Algorithm

Algorithm ParenMatch(X,n):

Input: An array X of n tokens, each of which is either a grouping symbol, a variable, an arithmetic operator, or a number

Output: true if and only if all the grouping symbols in X match

Let S be an empty stack

for i=0 to n-1 do
    if X[i] is an opening grouping symbol then
        S.push(X[i])
    else if X[i] is a closing grouping symbol then
        if S.isEmpty() then
            return false {nothing to match with}
        if S.pop() does not match the type of X[i] then
            return false {wrong type}
    if S.isEmpty() then
        return true {every symbol matched}
    else
        return false {some symbols were never matched}
Assignment 1 Q3. Minimum Value Stack

- You are designing a new class **MinStack** that specializes the java.util.Stack class to Comparable objects and provides a new method **min()** that will return the minimum value on the stack in **O(1)** time.
The Comparable Interface

- Part of the Collections Framework in java.util.
- Imposes a total ordering on the objects of a class that implements it.
- Objects can be compared using the compareTo method.
- obj1.compareTo(obj2) returns
  - Negative integer if obj1 < obj2
  - Positive integer if obj1 > obj2
  - 0 if obj1 = obj2
Linear Data Structures

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- Array Lists (Ch. 7.2)
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- Queues (Ch. 6.2)
- Linked Lists (Ch. 3.2 – 3.4)
The Queue ADT

- 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:
  - object enqueue(object): inserts an element at the end of the queue
  - object dequeue(): removes and returns the element at the front of the queue
- Auxiliary queue operations:
  - object first(): 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 first on an empty queue returns null
# Queue Example

<table>
<thead>
<tr>
<th>Operation</th>
<th>Output</th>
<th>Q</th>
</tr>
</thead>
<tbody>
<tr>
<td>enqueue(5)</td>
<td>–</td>
<td>(5)</td>
</tr>
<tr>
<td>enqueue(3)</td>
<td>–</td>
<td>(5, 3)</td>
</tr>
<tr>
<td>dequeue()</td>
<td>5</td>
<td>(3)</td>
</tr>
<tr>
<td>enqueue(7)</td>
<td>–</td>
<td>(3, 7)</td>
</tr>
<tr>
<td>dequeue()</td>
<td>3</td>
<td>(7)</td>
</tr>
<tr>
<td>first()</td>
<td>7</td>
<td>(7)</td>
</tr>
<tr>
<td>dequeue()</td>
<td>7</td>
<td>()</td>
</tr>
<tr>
<td>dequeue()</td>
<td>null</td>
<td>()</td>
</tr>
<tr>
<td>isEmpty()</td>
<td>true</td>
<td>()</td>
</tr>
<tr>
<td>enqueue(9)</td>
<td>–</td>
<td>(9)</td>
</tr>
<tr>
<td>enqueue(7)</td>
<td>–</td>
<td>(9, 7)</td>
</tr>
<tr>
<td>size()</td>
<td>2</td>
<td>(9, 7)</td>
</tr>
<tr>
<td>enqueue(3)</td>
<td>–</td>
<td>(9, 7, 3)</td>
</tr>
<tr>
<td>enqueue(5)</td>
<td>–</td>
<td>(9, 7, 3, 5)</td>
</tr>
<tr>
<td>dequeue()</td>
<td>9</td>
<td>(7, 3, 5)</td>
</tr>
</tbody>
</table>
Array-Based Queue

- Use an array of size $N$ in a circular fashion
- Two variables keep track of the front and rear
  - $f$ index of the front element
  - $r$ index immediately past the rear element
- Array location $r$ is kept empty

```
Q
0 1 2 f r
```

```
Q
0 1 2 r f
```

normal configuration

wrapped-around configuration
Queue Operations

• We use the modulo operator (remainder of division)

Algorithm `size()`
return \((r + N - f) \mod N\)

Algorithm `isEmpty()`
return \((f = r)\)
Queue Operations (cont.)

- Operation enqueue may throw an exception if the array is full

Algorithm enqueue(e)
if size() = N - 1 then
    throw IllegalStateException
else
    Q[r] ← e
    r ← (r + 1) mod N
Queue Operations (cont.)

- Operation dequeue throws an exception if the queue is empty.

Algorithm `dequeue()`

```plaintext
if isEmpty() then
    throw EmptyQueueException
else
    e ← Q[f]
    f ← (f + 1) mod N
    return e
```

![Queue Diagram](image)
Queue Interface in Java

- Java interface corresponding to our Queue ADT
- Assumes that `first()` and `dequeue()` return null if queue is empty

```java
public interface Queue<E> {
    int size();
    boolean isEmpty();
    E first();
    void enqueue(E e);
    E dequeue();
}
```
Array-based Implementation

```java
/** Implementation of the queue ADT using a fixed-length array. */
public class ArrayQueue<E> implements Queue<E> {
    // instance variables
    private E[] data; // generic array used for storage
    private int f = 0; // index of the front element
    private int sz = 0; // current number of elements

    // constructors
    public ArrayQueue() {this(CAPACITY);} // constructs queue with default capacity
    public ArrayQueue(int capacity) {
        data = (E[]) new Object[capacity]; // safe cast; compiler may give warning
    }

    // methods
    /** Returns the number of elements in the queue. */
    public int size() { return sz; }

    /** Tests whether the queue is empty. */
    public boolean isEmpty() { return (sz == 0); }
}
```
Array-based Implementation

```java
/** Inserts an element at the rear of the queue. */
public void enqueue(E e) throws java.lang.IllegalArgumentException {
    if (sz == data.length) throw new java.lang.IllegalArgumentException("Queue is full");
    int avail = (f + sz) % data.length;   // use modular arithmetic
    data[avail] = e;
    sz++;
}

/** Returns, but does not remove, the first element of the queue (null if empty). */
public E first() {
    if (isEmpty()) return null;
    return data[f];
}

/** Removes and returns the first element of the queue (null if empty). */
public E dequeue() {
    if (isEmpty()) return null;
    E answer = data[f];
    data[f] = null;    // dereference to help garbage collection
    f = (f + 1) % data.length;
    sz--;                
    return answer;
}
```
Comparison to `java.util.Queue`

- Our Queue methods and corresponding methods of `java.util.Queue`:

<table>
<thead>
<tr>
<th>Our Queue ADT</th>
<th>Interface <code>java.util.Queue</code></th>
</tr>
</thead>
<tbody>
<tr>
<td><code>enqueue(e)</code></td>
<td><code>add(e)</code></td>
</tr>
<tr>
<td><code>dequeue()</code></td>
<td><code>remove()</code></td>
</tr>
<tr>
<td><code>first()</code></td>
<td><code>element()</code></td>
</tr>
<tr>
<td><code>size()</code></td>
<td><code>size()</code></td>
</tr>
<tr>
<td><code>isEmpty()</code></td>
<td><code>isEmpty()</code></td>
</tr>
<tr>
<td></td>
<td>throws exceptions</td>
</tr>
<tr>
<td></td>
<td><code>offer(e)</code></td>
</tr>
<tr>
<td></td>
<td><code>peek()</code></td>
</tr>
</tbody>
</table>
Linear Data Structures

- Arrays (Ch. 3.1)
- Array Lists (Ch. 7.2)
- Stacks (Ch. 6.1)
- Queues (Ch. 6.2)
- Linked Lists (Ch. 3.2 – 3.4)
Linked Lists

• By virtue of their random access nature, **arrays** support non-structural read/write operations (e.g., `get(i)`, `set(i)`) in $O(1)$ time.

• Unfortunately, structural operations (e.g., `add(i,e)`, `remove(i)`) take $O(n)$ time.

• For some algorithms and inputs, structural operations may dominate the running time.

• For such cases, **linked lists** may be more appropriate.
Singly Linked List

- A singly linked list is a data structure consisting of a sequence of nodes.
- Each node stores:
  - element
  - link to the next node

```
A → B → C → D → ∅
```
Example Java Class for Singly-Linked Nodes

Private static class Node<E> {
    // Instance variables:
    private E element;
    private Node<E> next;

    /** Create a node with the given element and next node. */
    public Node(E e, Node<E> n) {
        element = e;
        next = n;
    }

    // Accessor methods:
    public E getElement() { return element; }
    public Node<E> getNext() { return next; }

    // Modifier methods:
    public void setNext(Node<E> n) { next = n; }
}
public class SinglyLinkedList<E> {
  // Instance variables:
  private Node head = null; //head node of list
  private Node tail = null; //tail node of list
  private int size = 0; //number of nodes in list
  /** Default constructor that creates an empty list. */
  public SinglyLinkedList() {}
  // update and search methods go here…
}
Inserting at the Head

1. Construct new node with new element
2. Have new node point to old head
3. Update head to point to new node
4. If list was initially empty, have to update tail as well.
Sept 29, 2015

End of Lecture
Removing at the Head

1. Update **head** to point to next node in the list

2. Allow garbage collector to reclaim the former first node

3. If list is now empty, have to update **tail** as well.
Example Application: Implementing a Stack with a Singly-Linked List

- Earlier we saw an array implementation of a stack.
- We could also implement a stack with a singly-linked list.
- The top element is stored at the first node of the list.
- The space used is $O(n)$ and each operation of the Stack ADT takes $O(1)$ time.

![Diagram of a singly-linked list with nodes and elements. The top element is stored at the first node.](image-url)
Implementing a Queue with a Singly-Linked List

- Just as for stacks, queue implementations can be based upon either arrays or linked lists.
- In a linked list implementation:
  - The front element is stored at the first node
  - The rear element is stored at the last node
- The space used is $O(n)$ and each operation of the Queue ADT takes $O(1)$ time
- Are there any advantages? Don’t have to worry about array overflow!
Assignment 1 Q1. Sparse Vectors

• In many applications, vectors are sparse, that is, they contain mainly 0 elements, e.g., [0 0 0 0 13.4 0 0 14.5 0 0 0 12.2].

• It is inefficient to represent such vectors as regular arrays. Instead, we consider a data structure that only represents data values that are non-zero.

• It will do this by maintaining both the value and the one-based position of each value in the vector. Thus the previous vector can be represented as [(5, 13.4), (8, 14.5), (12, 12.2)].

• We will represent this data structure as a singly-linked list, with elements containing both position indices and values.
Running Time

- Adding at the head is $O(1)$
- Removing at the head is $O(1)$
- **How about tail operations?**
Inserting at the Tail

1. Construct new node with new element
2. Have new node point to null
3. Have old last node point to new node
4. Update tail to point to new node
5. If list initially empty, have to update head as well.
Removing at the Tail

- Removing at the tail of a singly linked list is not efficient!
- There is no constant-time way to update the tail to point to the previous node
- How could we solve this problem?
Doubly Linked List

- Doubly-linked lists allow more flexible list management (constant time operations at both ends).
- Nodes store:
  - element
  - link to the previous node
  - link to the next node
- Special trailer and header (sentinel) nodes
Insertion

- **addBetween**(E e Node<E> predecessor, Node<E> successor) constructs a new node containing element e and inserts it between predecessor and successor nodes.

```
  predecessor      successor
  +------------+      +------------+
  |            |      |            |
  |            |      |            |
  |            |      |            |
  +------------+      +------------+
    A          B          C
```
**Insertion Algorithm**

```java
private void addBetween(E e, Node<E> predecessor, Node<E> successor) {
    Node<E> newest = new Node<>(e, predecessor, successor);
    predecessor.setNext(newest);  // link forward
    successor.setPrev(newest);    // link back
    size++;
}
```
Deletion

• **Remove**(Node<
E
> node) removes node from the list and returns the element that had been stored there.
Deletion Algorithm

```java
Private E remove(Node<E> node) {
    Node<E> predecessor = node.getPrev();
    Node<E> successor = node.getNext();
    predecessor.setNext(successor); {link forward}
    successor.setPrev(predecessor); {link back}
    size--;
    return node.getElement();
}
```
Running Time

• Insertion and Deletion of any given node takes $O(1)$ time.

• However, depending upon the application, finding the insertion location or the node to delete may take longer!
Linear Data Structures

- Arrays (Ch. 3.1)
- Array Lists (Ch. 7.2)
- Stacks (Ch. 6.1)
- Queues (Ch. 6.2)
- Linked Lists (Ch. 3.2 – 3.4)
Learning Outcomes

• Based on this lecture, you should:
  – Know the basic linear data structures
  – Be able to express each as an Abstract Data Type (ADT)
  – Be able to specify each of these ADTs as a Java interface.
  – Be able to outline the algorithms for creating, accessing and modifying each data structure
  – Be able to analyze the running time of these operations
  – Be able to identify particular applications for which each data structure would be suited.