

Data Structures and Algorithms

List ADT & Linked Lists

Acknowledgement

- The contents of these slides have origin from School of Computing, National University of Singapore.
- We greatly appreciate support from Mr. Aaron Tan Tuck Choy, and Dr. Low Kok Lim for kindly sharing these materials.

Policies for students

- These contents are only used for students PERSONALLY.
- Students are NOT allowed to modify or deliver these contents to anywhere or anyone for any purpose.

Recording of modifications

- Course website address is changed to <http://sakai.it.tdt.edu.vn>
- Slides “Practice Exercises” are eliminated.
- Course codes cs1010, cs1020, cs2010 are placed by 501042, 501043, 502043 respectively.

Objectives

1

- Able to define a List ADT

2

- Able to implement a List ADT with array

3

- Able to implement a List ADT with linked list

4

- Able to use Java API LinkedList class

References



Book

- **List ADT:** Chapter 4, pages 227 to 233
- An array-based implementation: Chapter 4, pages 250 to 257
- **Linked Lists:** Chapter 5, pages 265 to 325



IT-TDT Sakai → 501043 website
→ Lessons

- <http://sakai.it.tdt.edu.vn>

Programs used in this lecture

- ❑ For Array implementation of List:
 - ListInterface.java
 - ListUsingArray.java, TestListUsingArray.java
- ❑ For Linked List implementation of List:
 - ListNode.java
 - ListInterface.java (same ListInterface.java as in array implementation)
 - BasicLinkedList.java, TestBasicLinkedList1.java, TestBasicLinkedList2.java
 - EnhancedListInterface.java
 - EnhancedLinkedList.java, TestEnhancedLinkedList.java
 - TailedLinkedList.java, TestTailedLinkedList.java

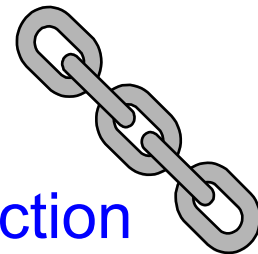
Outline

1. Use of a List (Motivation)
 - List ADT
2. List ADT Implementation via Array
 - Adding and removing elements in an array
 - Time and space efficiency
3. List ADT Implementation via Linked Lists
 - Linked list approach
 - ListNode class: forming a linked list with ListNode
 - BasicLinkedList
4. More Linked Lists
 - EnhancedLinkedList, TailedLinkedList
5. Other Variants
 - CircularLinkedList, DoublyLinkedList
6. Java API: LinkedList class
7. Summary

1 Use of a List

Motivation

Motivation



- ❑ **List** is one of the most basic types of data collection
 - For example, list of groceries, list of modules, list of friends, etc.
 - In general, we keep items of the **same type (class)** in one list
- ❑ **Typical Operations on a data collection**
 - **Add** data
 - **Remove** data
 - **Query** data
 - The details of the operations vary from application to application. The overall theme is the **management of data**



ADT of a List (1/3)

- ❑ A list ADT is a dynamic linear data structure
 - A collection of data items, accessible one after another starting from the beginning (head) of the list
- ❑ Examples of List ADT operations:
 - Create an empty list
 - Determine whether a list is empty
 - Determine number of items in the list
 - Add an item at a given position
 - Remove an item at a position
 - Remove all items
 - Read an item from the list at a position
- ❑ The next slide on the basic list interface does not have all the above operations... we will slowly build up these operations in list beyond the basic list.

You will learn non-linear data structures such as trees and graphs in 502043.

ADT of a List (2/3)

ListInterface.java

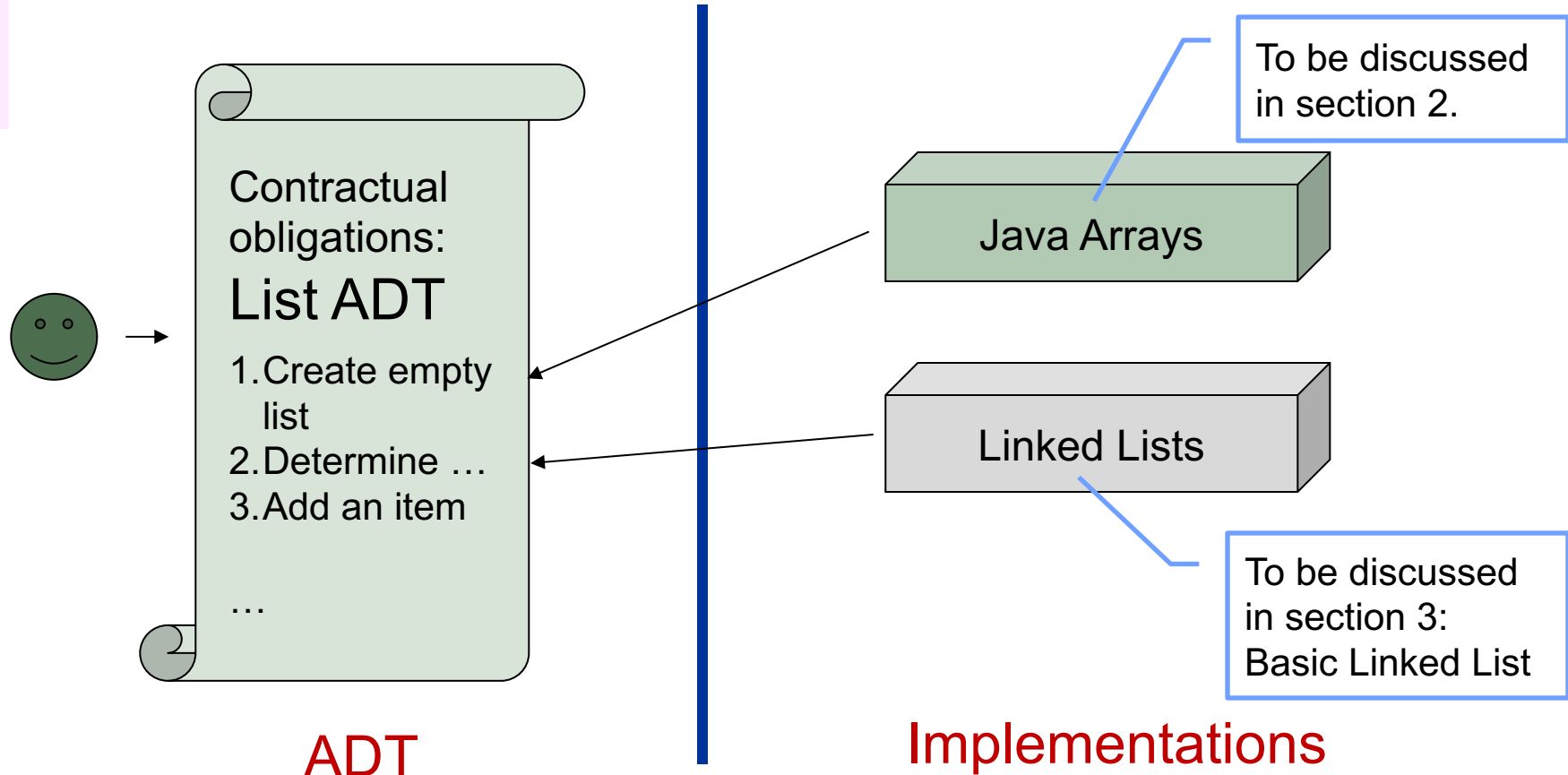
```
import java.util.*;

public interface ListInterface <E> {
    public boolean isEmpty();
    public int size();
    public E getFirst() throws NoSuchElementException;
    public boolean contains(E item);
    public void addFirst(E item);
    public E removeFirst()
                throws NoSuchElementException;
    public void print();
}
```

- ❑ The **ListInterface** above defines the operations (methods) we would like to have in a List ADT
- ❑ The operations shown here are just a small sample. An actual List ADT usually contains more operations.

ADT of a List (3/3)

- We will examine 2 implementations of list ADT, both using the **ListInterface** shown in the previous slide



2 List Implementation via Array

Fixed-size list



2. List Implementation: Array (1/9)

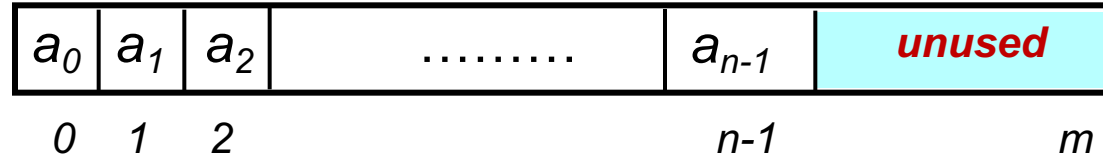
- This is a straight-forward approach

- Use Java array of a sequence of n elements

num_nodes

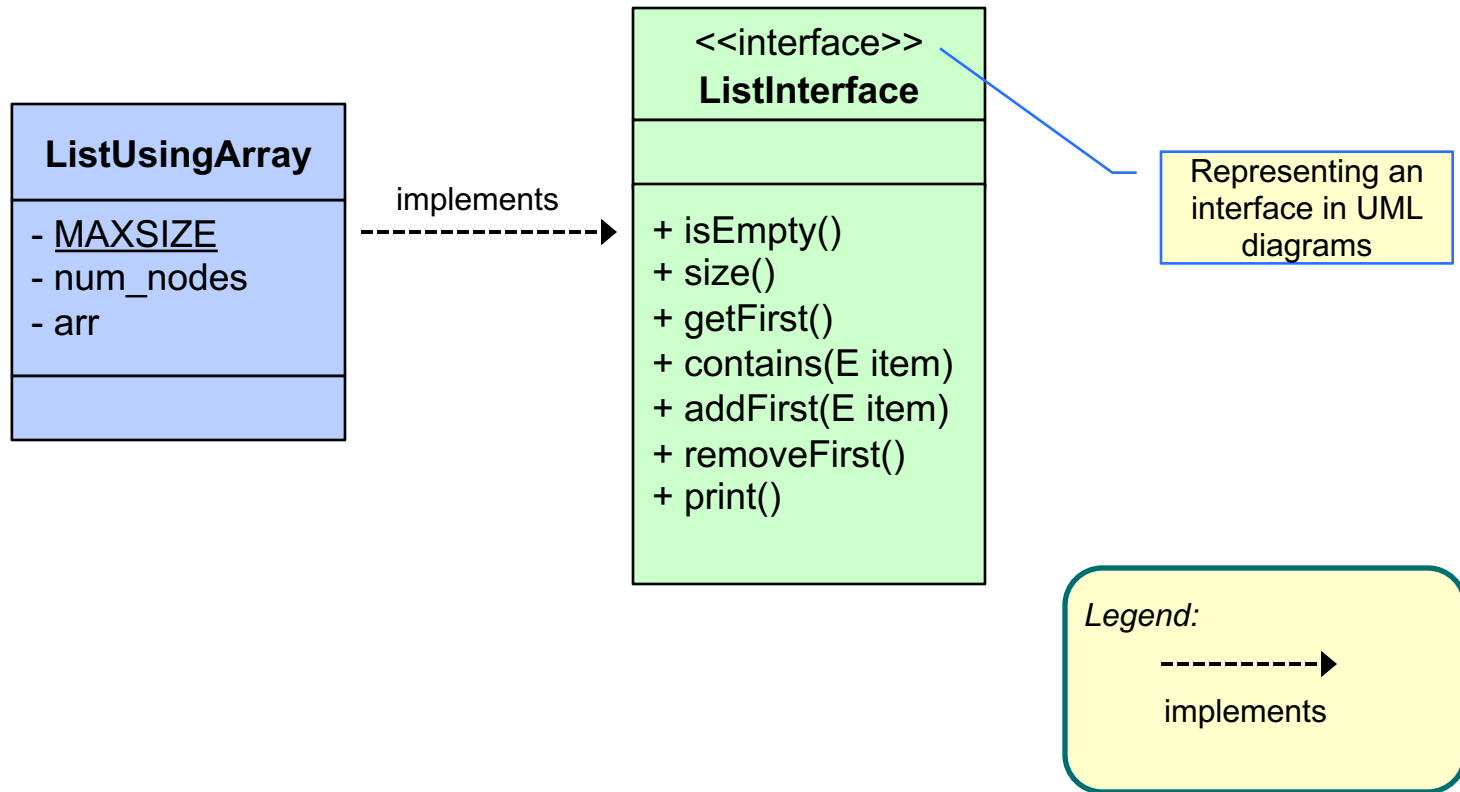
n

arr : array[0..m] of locations



2. List Implementation: Array (2/9)

- ❑ We now create a class `ListUsingArray` as an implementation of the interface `ListInterface` (a user-defined interface, as defined in [slide 9](#))



2. List Implementation: Array (3/9)

ListUsingArray.java

```
import java.util.*;

class ListUsingArray <E> implements ListInterface <E> {
    private static final int MAXSIZE = 1000;
    private int num_nodes = 0;
    private E[] arr = (E[]) new Object[MAXSIZE];

    public boolean isEmpty() { return num_nodes==0; }
    public int size()        { return num_nodes; }

    public E getFirst() throws NoSuchElementException {
        if (num_nodes == 0)
            throw new NoSuchElementException("can't get from an empty list");
        else return arr[0];
    }

    public boolean contains(E item) {
        for (int i = 0; i < num_nodes; i++)
            if (arr[i].equals(item)) return true;

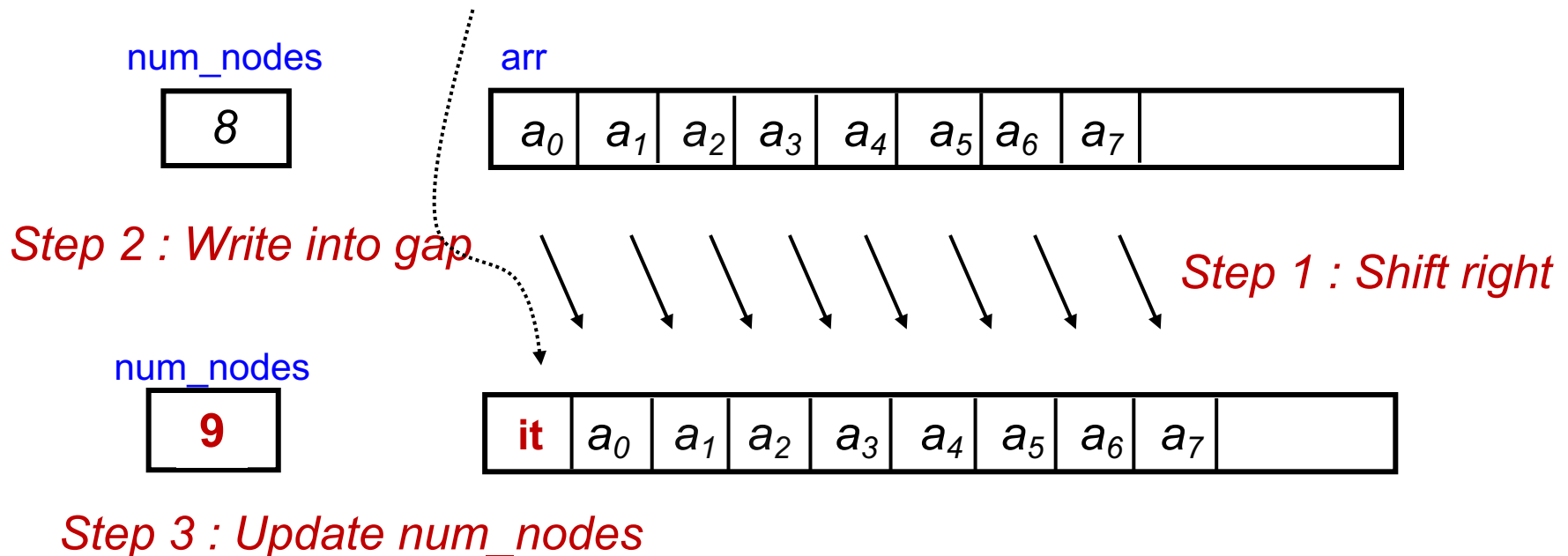
        return false;
    }
}
```

Code continued in [slide 17](#)

2. List Implementation: Array (4/9)

- For **insertion into first position**, need to shift “right” (starting from the last element) to create room

Example: **addFirst(“it”)**



2. List Implementation: Array (5/9)

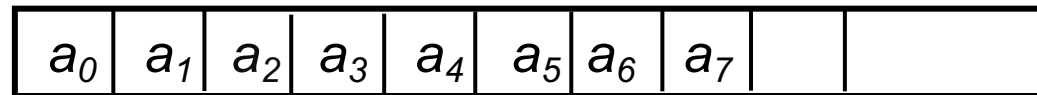
- ❑ For **deletion of first element**, need to shift “left” (starting from the first element) to close gap

Example: **removeFirst()**

num_nodes

8

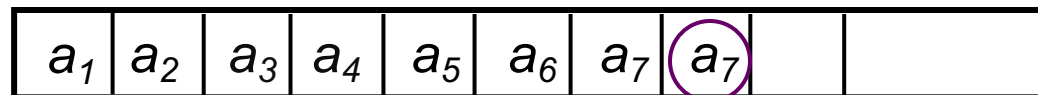
arr



Step 1 : Close Gap

num_nodes

7



Step 2 : Update num_nodes

unused

Need to maintain **num_nodes** so that program would not access beyond the valid data.

2. List Implementation: Array (6/9)

```
public void addFirst(E item) throws IndexOutOfBoundsException {
    if (num_nodes == MAXSIZE)
        throw new IndexOutOfBoundsException("insufficient space for add");
    for (int i = num_nodes-1; i >= 0; i--)
        arr[i+1] = arr[i]; // to shift elements to the right

    arr[0] = item;
    num_nodes++; // update num_nodes
}

public E removeFirst() throws NoSuchElementException {
    if (num_nodes == 0)
        throw new NoSuchElementException("can't remove from an empty list");
    else {
        E tmp = arr[0];
        for (int i = 0; i < num_nodes-1; i++)
            arr[i] = arr[i+1]; // to shift elements to the left
        num_nodes--; // update num_nodes
        return tmp;
    }
}
```

print() method not shown
here. Refer to program.

ListUsingArray.java

2. Testing Array Implementation (7/9)

```
import java.util.*;

public class TestListUsingArray {
    public static void main(String [] args)
        throws NoSuchElementException {
        ListUsingArray <String> list = new ListUsingArray <String>();
        list.addFirst("aaa");
        list.addFirst("bbb");
        list.addFirst("ccc");
        list.print();

        System.out.println("Testing removal");
        list.removeFirst();
        list.print();

        if (list.contains("aaa"))
            list.addFirst("xxxx");
        list.print();
    }
}
```

TestListUsingArray.java

2. Analysis of Array Implⁿ of List (8/9)

- Question: Time Efficiency?
 - Retrieval: `getFirst()`
 - Always fast with 1 read operation
 - Insertion: `addFirst(E item)`
 - Shifting of all n items – bad!
 - Insertion: `add(int index, E item)`
 - Inserting into the specified position (not shown in ListUsingArray.java)
 - Best case: No shifting of items (add to the last place)
 - Worst case: Shifting of all items (add to the first place)
 - Deletion: `removeFirst(E item)`
 - Shifting of all n items – bad!
 - Deletion: `remove(int index)`
 - Delete the item at the specified position (not shown in ListUsingArray.java)
 - Best case: No shifting of items (delete the last item)
 - Worst case: Shifting of all items (delete the first item)

2. Analysis of Array Implⁿ of List (9/9)

- Question: What is the **Space Efficiency**?
 - Size of array collection limited by MAXSIZE
 - Problems
 - We don't always know the maximum size ahead of time
 - If MAXSIZE is too liberal, unused space is wasted
 - If MAXSIZE is too conservative, easy to run out of space
- Idea: make MAXSIZE a variable, and create/copy to a larger array whenever the array runs out of space
 - No more limits on size
 - But copying overhead is still a problem
- **When to use such a list?**
 - For a fixed-size list, an array is good enough!
 - For a variable-size list, where dynamic operations such as insertion/deletion are common, an array is a poor choice; better alternative – **Linked List**

3 List Implementation via Linked List

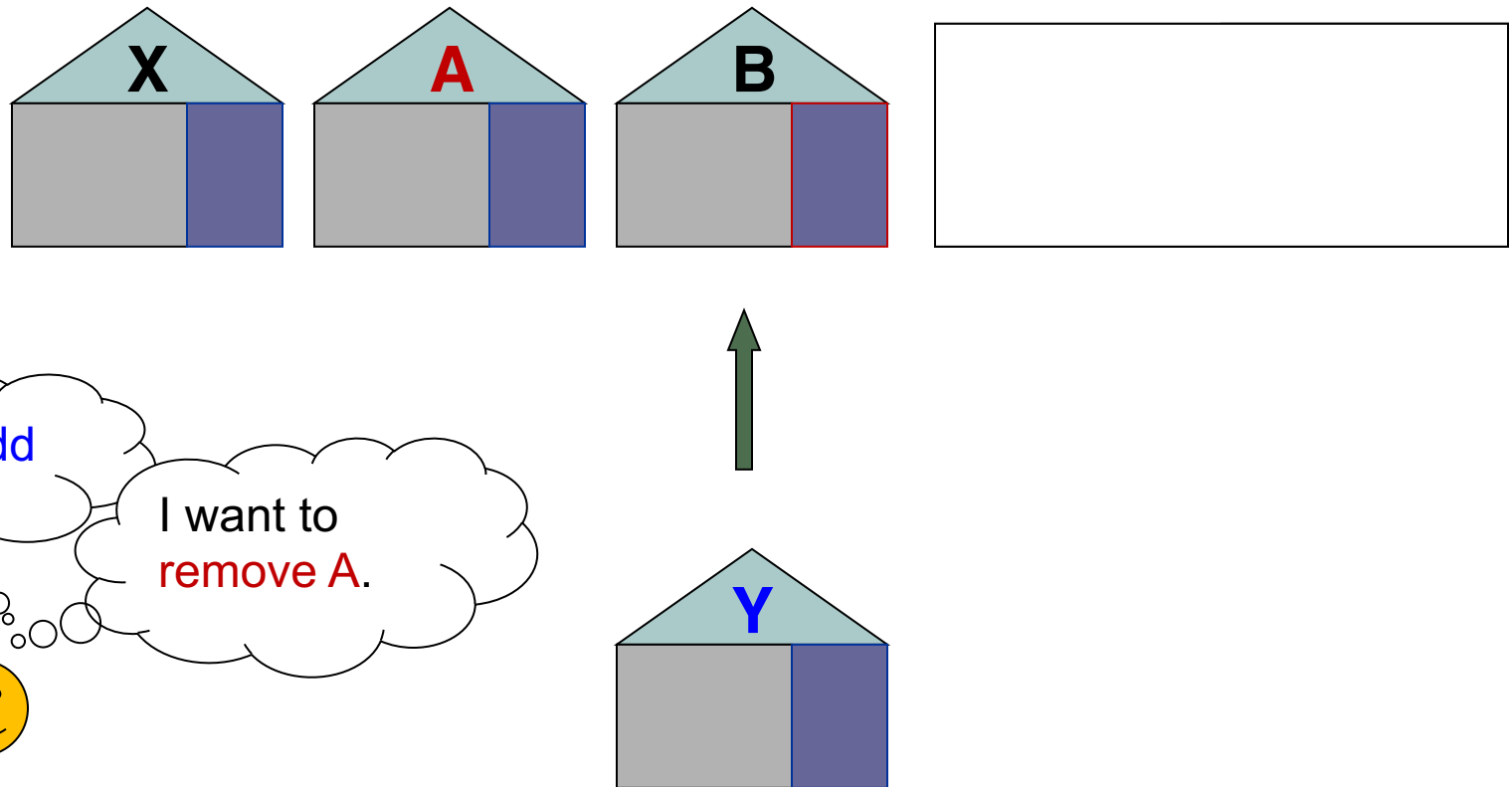
Variable-size list



3.1 List Implementation: Linked List (1/3)

Recap when using an array...

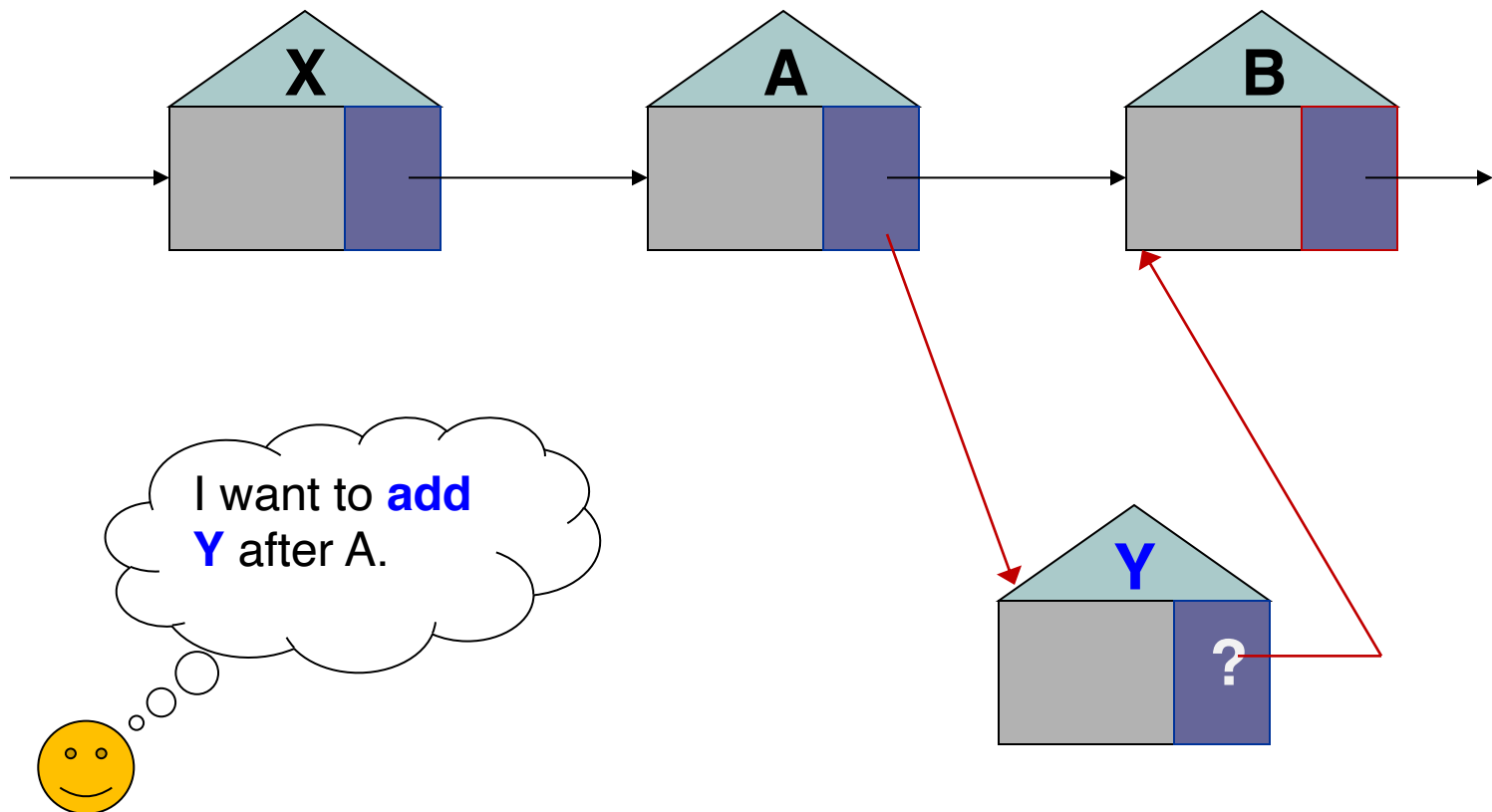
- X, A, B are elements of an array
- Y is new element to be added



3.1 List Implementation: Linked List (2/3)

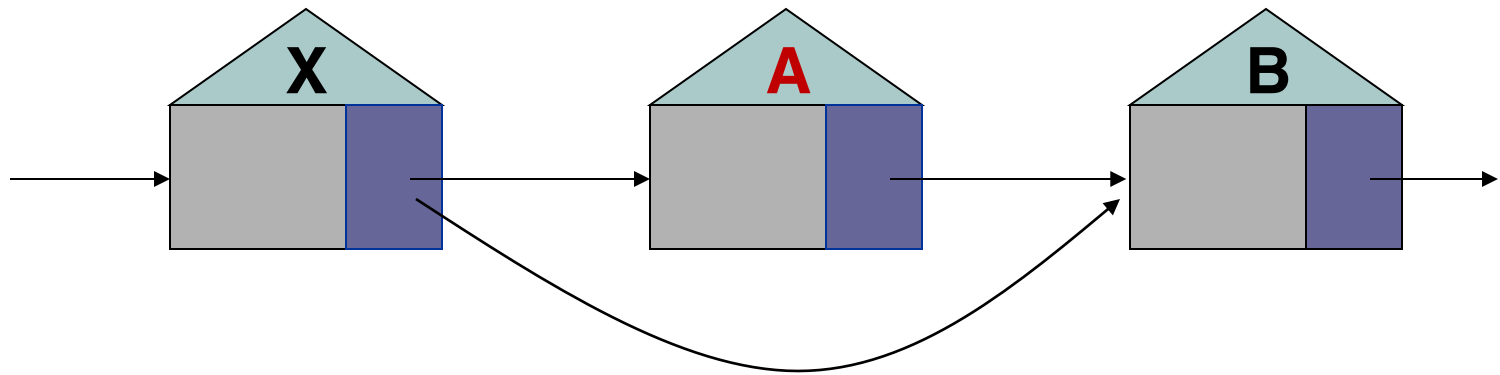
□ Now, we see the **(add)** action with linked list...

- X, A, B are nodes of a linked list
- Y is new node to be added



3.1 List Implementation: Linked List (3/3)

□ Now, we see the (remove) action with linked list...

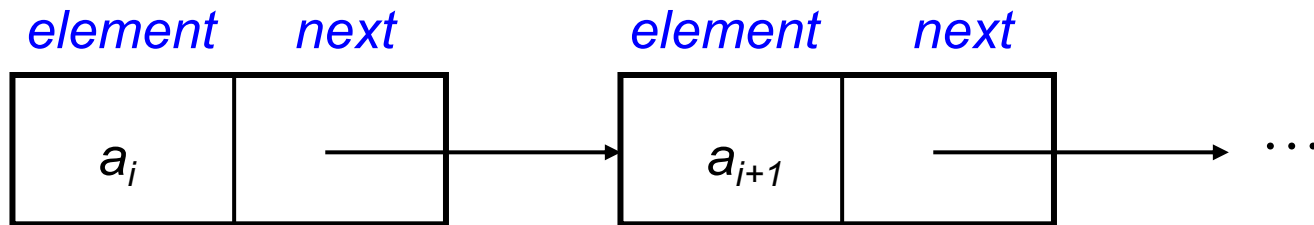


Node A becomes a *garbage*. To be removed during garbage collection.

3.2 Linked List Approach (1/4)

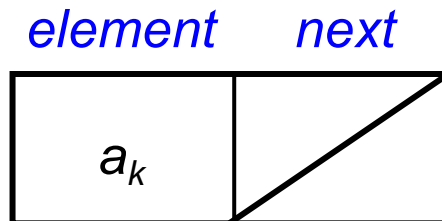
❑ Idea

- ❑ Each element in the list is stored in a *node*, which also contains a *next pointer*
- ❑ Allow elements in the list to occupy *non-contiguous* memory
- ❑ Order the nodes by associating each with its neighbour(s)



This is one node
of the collection...

... and this one comes after it in the
collection (most likely not occupying
contiguous memory that is next to the
previous node).



Next pointer of this node is “null”,
i.e. it has no next neighbour.

3.2 Linked List Approach (2/4)

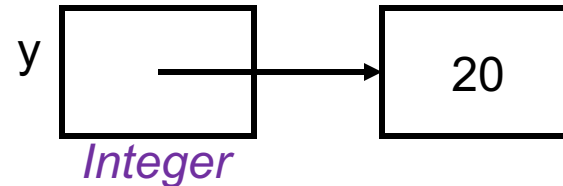
❑ Recap: Object References (1/2)

- ❑ Note the difference between primitive data types and reference data types

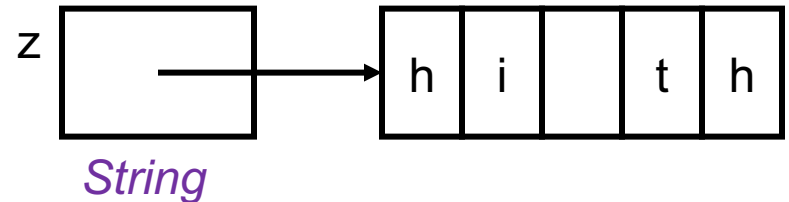
```
int x = 20;
```



```
Integer y = new Integer(20);
```



```
String z = new String("hi th");
```



- ❑ An instance (object) of a class only comes into existence (constructed) when the `new` operator is applied
- ❑ A reference variable only contains a reference or pointer to an object.

3.2 Linked List Approach (3/4)

❑ Recap: Object References (2/2)

❑ Look at it in more details:

```
Integer y = new Integer(20);
```

```
Integer w;
```

```
w = new Integer(20);
```

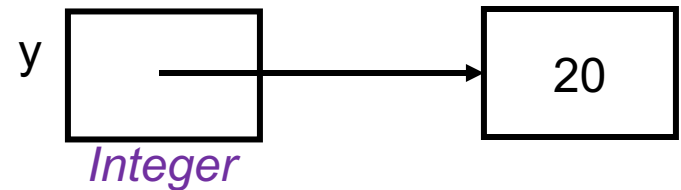
```
if (w == y)
```

```
    System.out.println("1. w == y");
```

```
w = y;
```

```
if (w == y)
```

```
    System.out.println("2. w == y");
```



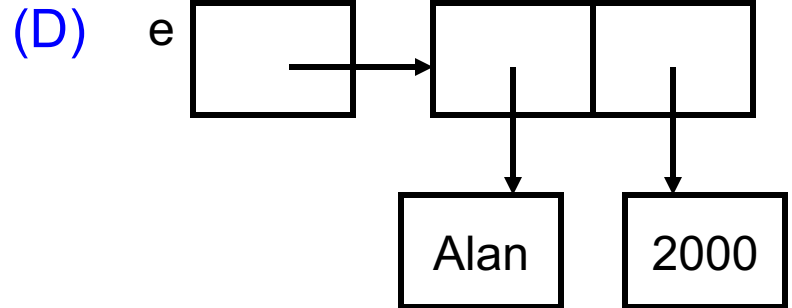
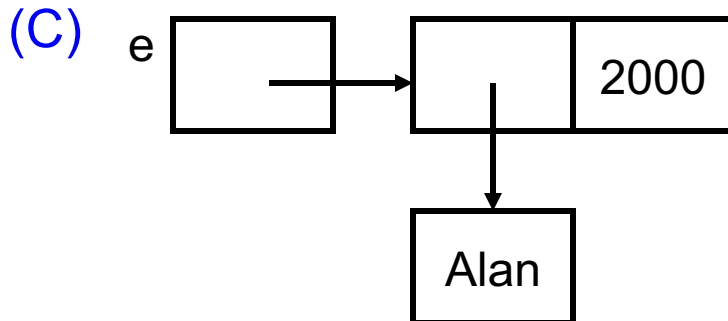
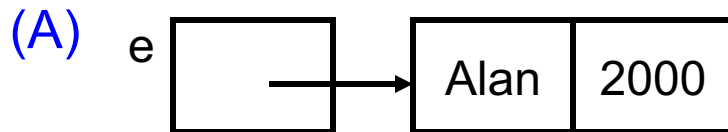
❑ Output:

3.2 Linked List Approach (4/4)

❑ Quiz: Which is the right representation of **e**?

```
class Employee {  
    private String name;  
    private int salary;  
    // etc.  
}
```

Employee **e** = new Employee("Alan", 2000);



3.3 ListNode (using generic)

NOTE

ListNode.java

```
class ListNode <E> {
    /* data attributes */
    private E element;
    private ListNode <E> next;

    /* constructors */
    public ListNode(E item) { this(item, null); }
    /*{
    Element = item;
    Next = null;
    }*/

    public ListNode(E item, ListNode <E> n) {
        element = item;
        next = n;
    }

    /* get the next ListNode */
    public ListNode <E> getNext() { return next; }

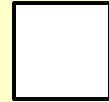
    /* get the element of the ListNode */
    public E getElement() { return element; }

    /* set the next reference */
    public void setNext(ListNode <E> n) { next = n; }
```

element



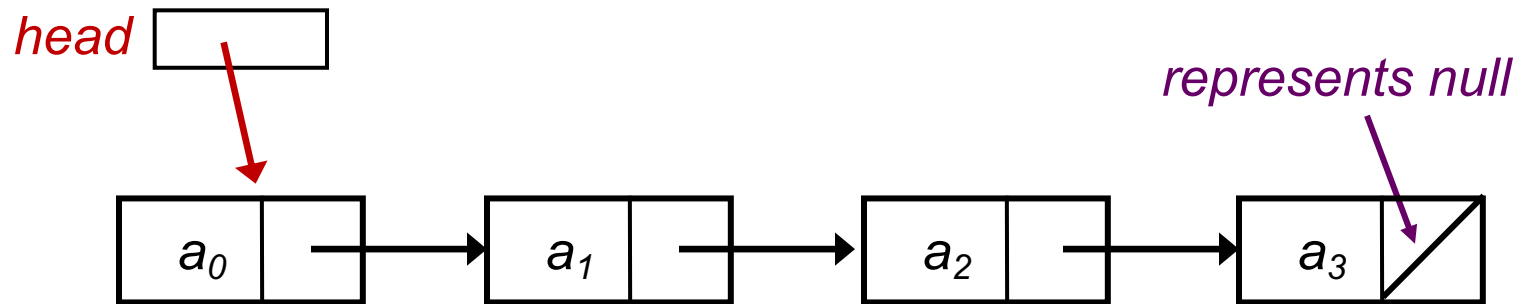
next



Mark this slide – You may need to refer to it later when we study the different variants of linked list.

3.4 Forming a Linked List (1/3)

□ For a sequence of 4 items $\langle a_0, a_1, a_2, a_3 \rangle$



We need a *head* to indicate where the first node is. From the *head* we can get to the rest.

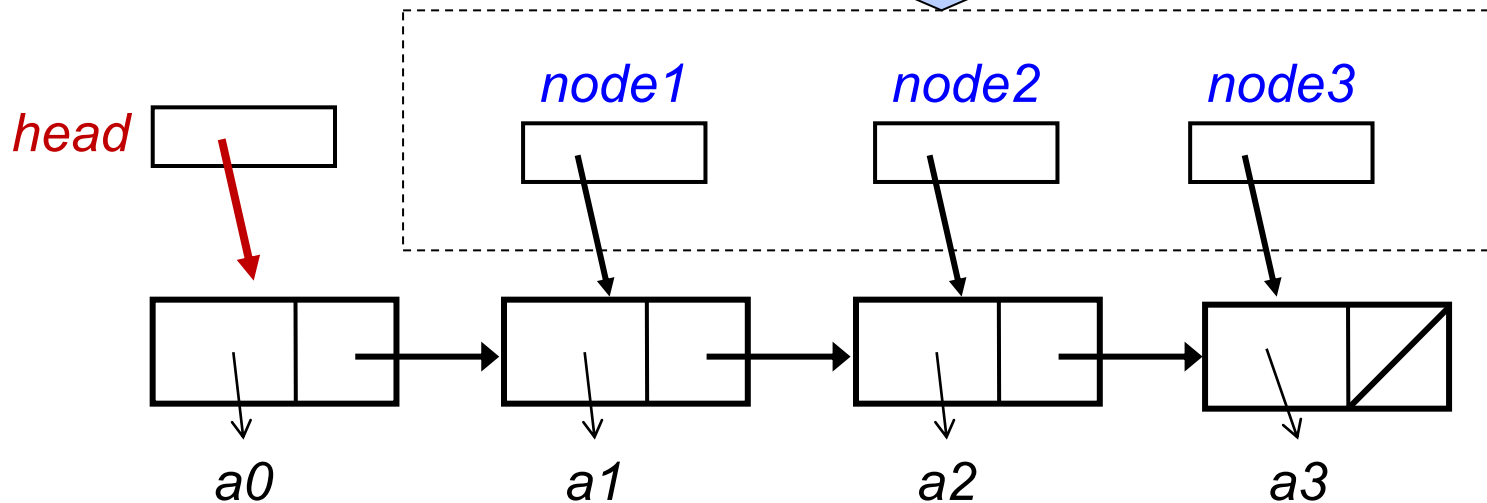
3.4 Forming a Linked List (2/3)

□ For a sequence of 4 items $\langle a_0, a_1, a_2, a_3 \rangle$

```
ListNode <String> node3 = new ListNode <String>("a3", null);  
ListNode <String> node2 = new ListNode <String>("a2", node3);  
ListNode <String> node1 = new ListNode <String>("a1", node2);  
ListNode <String> head  = new ListNode <String>("a0", node1);
```

Can the code be rewritten without
using these object references
`node1`, `node2`, `node3`?

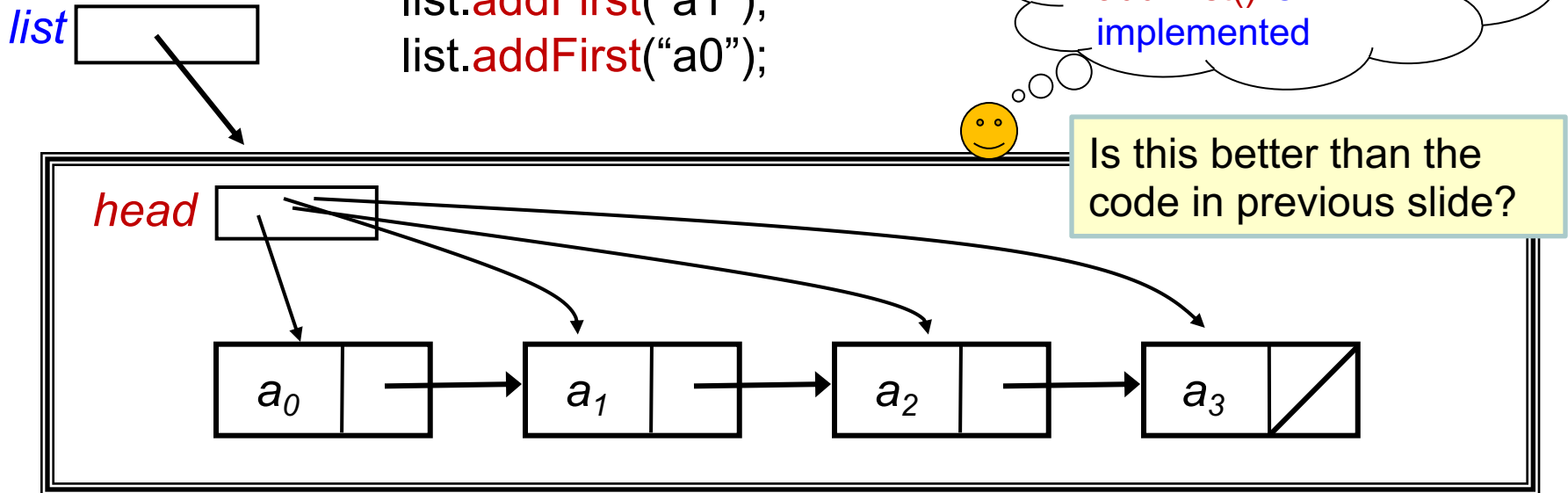
No longer needed
after list is built.



3.4 Forming a Linked List (3/3)

- Alternatively we can form the linked list as follows:
 - For a sequence of 4 items $\langle a_0, a_1, a_2, a_3 \rangle$, we can build as follows:

```
LinkedList <String> list = new LinkedList <String>();  
list.addFirst("a3");  
list.addFirst("a2");  
list.addFirst("a1");  
list.addFirst("a0");
```



3.5 Basic Linked List (1/7)

■ Using `ListNode` to define `BasicLinkedList`

BasicLinkedList.java

```
import java.util.*;
class BasicLinkedList <E> implements ListInterface <E> {
    private ListNode <E> head = null;
    private int num_nodes = 0;

    public boolean isEmpty() { return (num_nodes == 0); }

    public int size() { return num_nodes; }

    public E getFirst() throws NoSuchElementException {
        if (head == null)
            throw new NoSuchElementException("can't get from an empty list");
        else return head.getElement();
    }

    public boolean contains(E item) {
        for (ListNode <E> n = head; n != null; n = n.getNext())
            if (n.getElement().equals(item)) return true;
        return false;
    }
}
```

`getElement()` and
`getNext()` are methods in
`ListNode` class ([slide 29](#))

3.5 Basic Linked List (2/7)

■ The adding and removal of first element

BasicLinkedList.java

```
public void addFirst(E item) {  
    head = new ListNode <E> (item, head);  
    //ListNode p = new ListNode (item);  
    //p.setNext(head); //p.next = head  
    //head = p;  
  
    num_nodes++;  
}
```


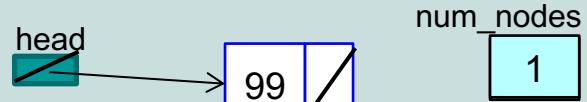
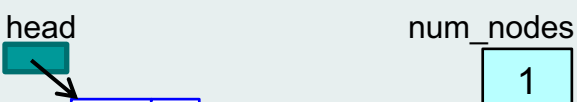
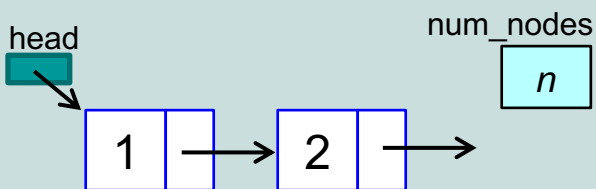
```
public E removeFirst() throws NoSuchElementException {  
    ListNode <E> ln;  
    if (head == null)  
        throw new NoSuchElementException("can't r  
    else {  
        ln = head;  
        head = head.getNext();  
        num_nodes--;  
        return ln.getElement();  
    }  
}
```

getElement() and
getNext() are methods in
ListNode class ([slide 29](#))

3.5 Basic Linked List (3/7)


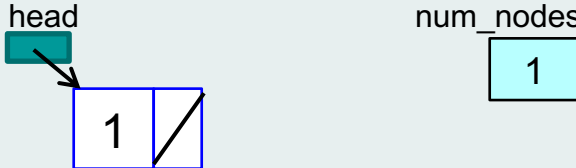
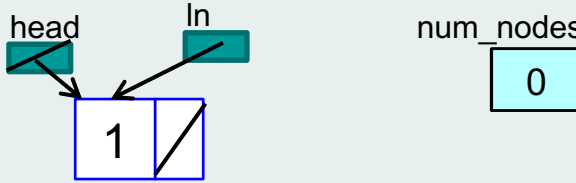
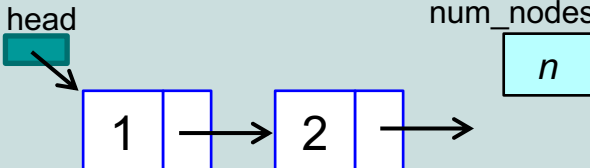
■ The `addFirst()` method

```
public void addFirst(E item) {
    head = new ListNode <E> (item, head);
    num_nodes++;
}
```

Case	Before: list	After: list.addFirst(99)
0 item	 <p>head points to null, num_nodes = 0</p>	 <p>head points to node with 99, num_nodes = 1</p>
1 item	 <p>head points to node with 1, num_nodes = 1</p>	
2 or more items	 <p>head points to node with 1, which points to node with 2, num_nodes = n</p>	

3.5 Basic Linked List (4/7)

- The `removeFirst()` method

Case	Before: list	After: list.removeFirst()
0 item		can't remove
1 item		
2 or more items		

```

public E removeFirst() throws NoSuchElementException {
    ListNode <E> ln;
    if (head == null)
        throw new NoSuchElementException("can't remove");
    else {
        ln = head; head = head.getNext(); num_nodes--;
        return ln.getElement();
    }
}

```

3.5 Basic Linked List (5/7)

■ Printing of the linked list

BasicLinkedList.java

```
public void print() throws NoSuchElementException {
    if (head == null)
        throw new NoSuchElementException("Nothing to print...");

    ListNode <E> ln = head;
    System.out.print("List is: " + ln.getElement());
    for (int i=1; i < num_nodes; i++) {
        ln = ln.getNext();
        System.out.print(", " + ln.getElement());
    }
    System.out.println(".");
}
```


3.5 Test Basic Linked List #1 (6/7)

■ Example use #1

TestBasicLinkedList1.java

```
import java.util.*;

public class TestBasicLinkedList1 {
    public static void main(String [] args)
        throws NoSuchElementException {
        BasicLinkedList <String> list = new BasicLinkedList <String>();
        list.addFirst("aaa");
        list.addFirst("bbb");
        list.addFirst("ccc");
        list.print();

        System.out.println("Testing removal");
        list.removeFirst();
        list.print();

        if (list.contains("aaa"))
            list.addFirst("xxxx");
        list.print();
    }
}
```

3.5 Test Basic Linked List #2 (7/7)

■ Example use #2

TestBasicLinkedList2.java

```
import java.util.*;

public class TestBasicLinkedList2 {
    public static void main(String [] args)
        throws NoSuchElementException {
        BasicLinkedList <Integer> list = new BasicLinkedList <Integer>();

        list.addFirst(34);
        list.addFirst(12);
        list.addFirst(9);
        list.print();

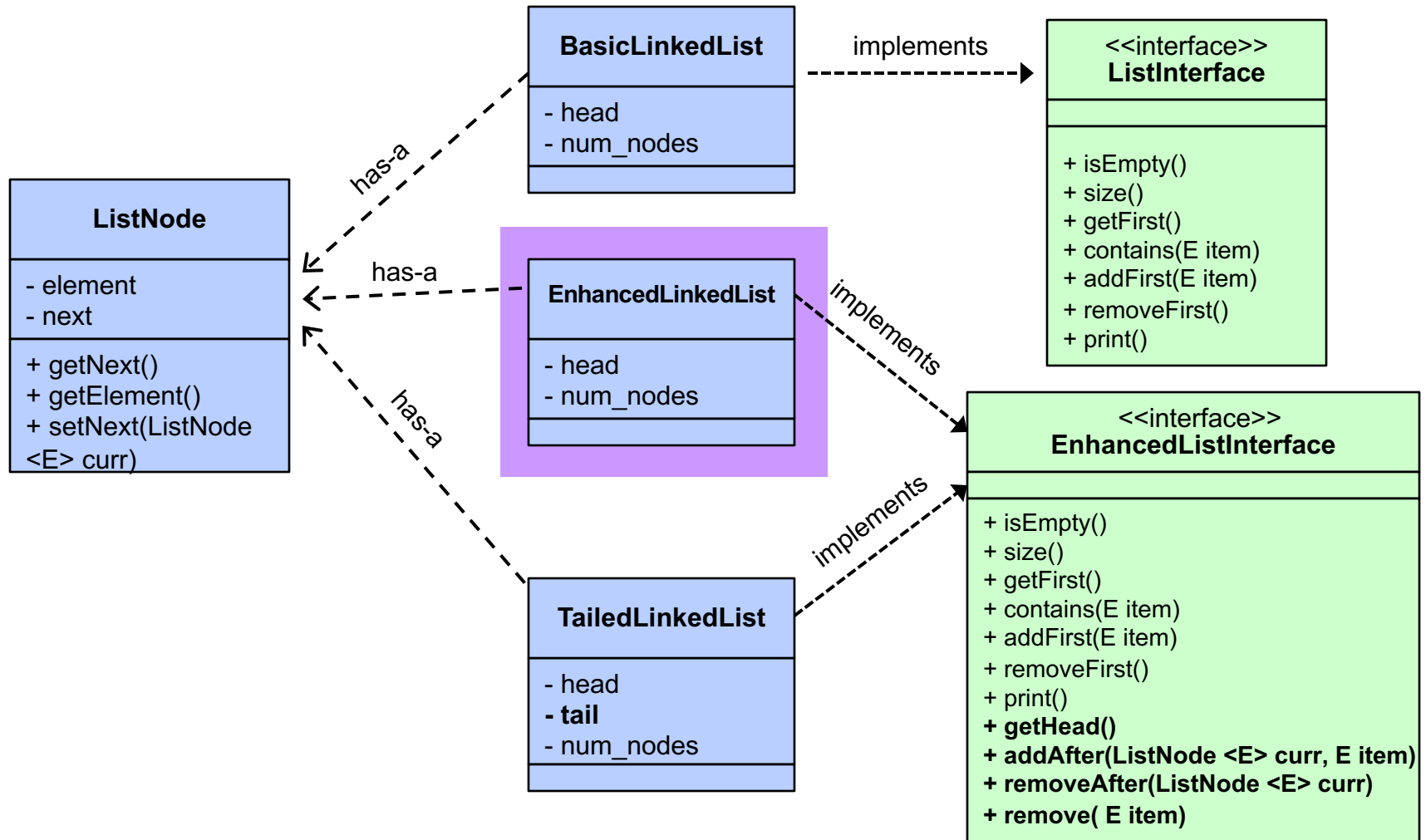
        System.out.println("Testing removal");
        list.removeFirst();
        list.print();
    }
}
```

4 More Linked Lists

Exploring variants of linked list

4. Linked Lists: Variants

OVERVIEW!



4.1 Enhanced Linked List (1/11)

- We explore different implementations of Linked List
 - Basic Linked List, Tailed Linked List, Circular Linked List, Doubly Linked List, etc.
- When nodes are to be inserted to the middle of the linked list, BasicLinkedList (BLL) is not good enough.
- For example, BLL offers only insertion at the front of the list. If the items in the list must always be sorted according to some key values, then we must be able to insert at the right place.
- We will enhance BLL to include some additional methods. We shall call this **Enhanced Linked List** (ELL).
 - (Note: We could have made ELL a subclass of BLL, but here we will create ELL from scratch instead.)

4.1 Enhanced Linked List (2/11)

- We use a new interface file:

EnhancedListInterface.java

```
import java.util.*;

public interface EnhancedListInterface <E> {

    public boolean isEmpty();
    public int size();
    public E getFirst() throws NoSuchElementException;
    public boolean contains(E item);
    public void addFirst(E item);
    public E removeFirst() throws NoSuchElementException;
    public void print();

    public ListNode <E> getHead();
    public void addAfter(ListNode <E> current, E item);
    public E removeAfter(ListNode <E> current)
        throws NoSuchElementException;
    public E remove(E item) throws NoSuchElementException;
}
```

New

```

import java.util.*;
class EnhancedLinkedList <E>
    implements EnhancedListInterface <E> {
    private ListNode <E> head = null;
    private int num_nodes = 0;

    public boolean isEmpty() { return (num_nodes == 0); }
    public int size() { return num_nodes; }
    public E getFirst() { ... }
    public boolean contains(E item) { ... }
    public void addFirst(E item) { ... }
    public E removeFirst() throws NoSuchElementException { ... };
    public void print() throws NoSuchElementException { ... }
    public ListNode <E> getHead() { return head; }
    public void addAfter(ListNode <E> current, E item) {
        if (current != null)
            //current.setNext(new ListNode <E> (item,
//current.getNext()));
    }

    ListNode<E> p = new ListNode<E>(item);
    p.setNext(current.getNext());
    current.setNext(p);

    else // insert item at front
//    head = new ListNode <E> (item, head);
    addFirst(item);


    num_nodes++;
}

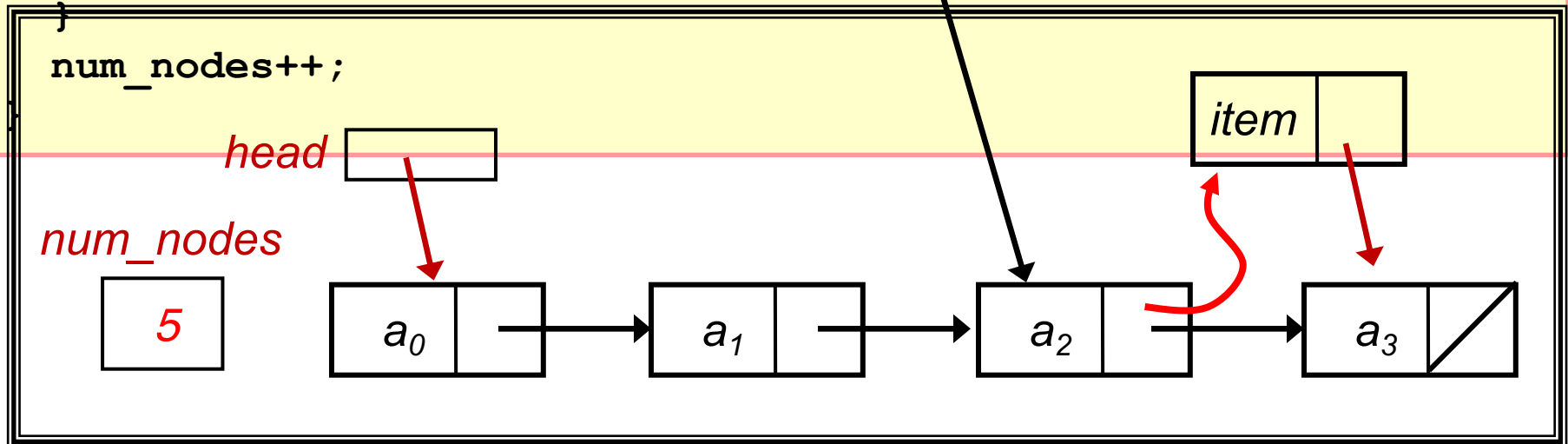
```

Same as in
BasicLinkedList.java

To continue on next slide

4.1 Enhanced Linked List (4/11)

```
public void addAfter(ListNode <E> current, E item) {  
    if (current != null) {  
        // current.setNext(new ListNode <E>(item, current.getNext()));  
        ListNode<E> p = new ListNode<E>(item);  
        p.setNext(current.getNext());  
        current.setNext(p);  
    } else { // insert item at front  
        head = new ListNode <E> current  head;  
    }  
}
```



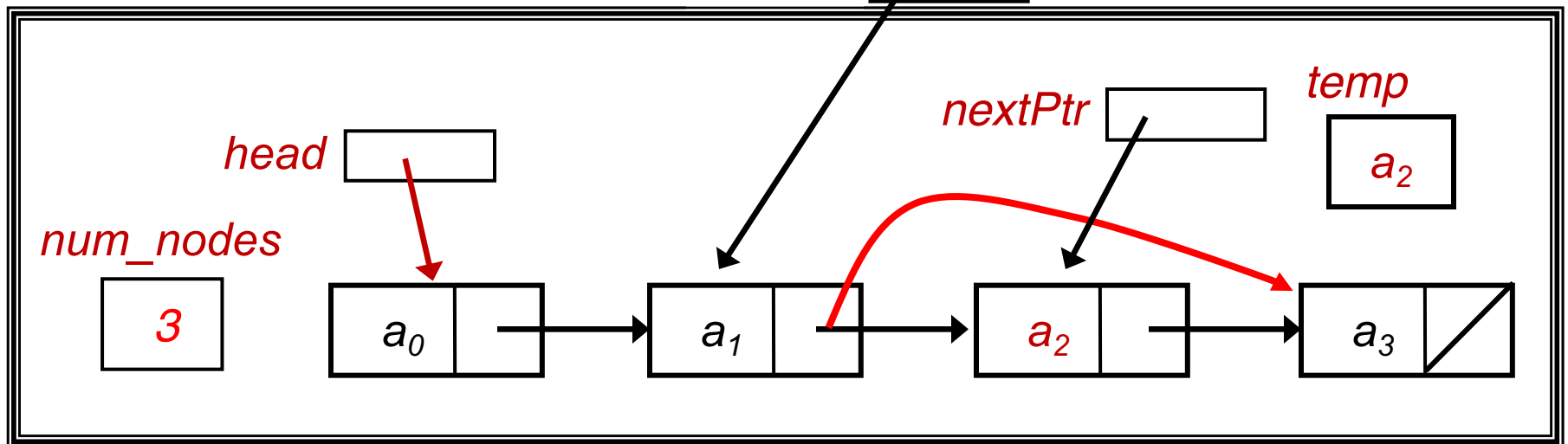
4.1 Enhanced Linked List (5/11)

EnhancedLinkedList.java

```
public E removeAfter(ListNode <E> current)
    throws NoSuchElementException {
    E temp;
    if (current != null) {
        ListNode <E> nextPtr = current.getNext();
        if (nextPtr != null) {
            temp = nextPtr.getElement();
            current.setNext(nextPtr.getNext());
            num_nodes--;
            return temp;
        } else throw new NoSuchElementException("No next node to remove");
    } else { // if current is null, assume we want to remove head
        if (head != null) {
            temp = head.getElement();
            head = head.getNext();
            num_nodes--;
            return temp;
        } else throw new NoSuchElementException("No next node to remove");
    }
}
```

4.1 Enhanced Linked List (6/11)

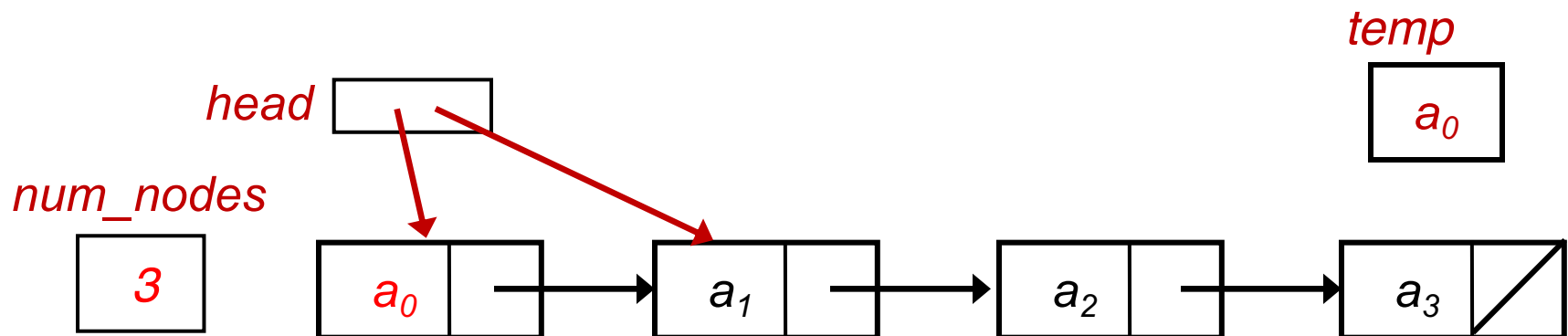
```
public E removeAfter(ListNode <E> current) throws ... {
    E temp;
    if (current != null) {
        ListNode<E> nextPtr = current.getNext();
        if (nextPtr != null) {
            temp = nextPtr.getElement();
            current.setNext(nextPtr.getNext());
            num_nodes--;
            return temp;
        } else throw new NoSuchElementException("...");
    } else { ... }
}
```



4.1 Enhanced Linked List (7/11)

```
public E removeAfter(ListNode <E> current) throws ... {
    E temp;
    if (current != null) {
        ...
    } else { // if current is null, we want to remove head
        if (head != null) {
            temp = head.getElement();
            head = head.getNext();
            num_nodes--;
            return temp;
        } else throw new NoSuchElementException("...");
    }
}
```

current null



4.1 Enhanced Linked List (8/11)

- remove(E item)
 - Search for item in list
 - Re-using removeAfter() method

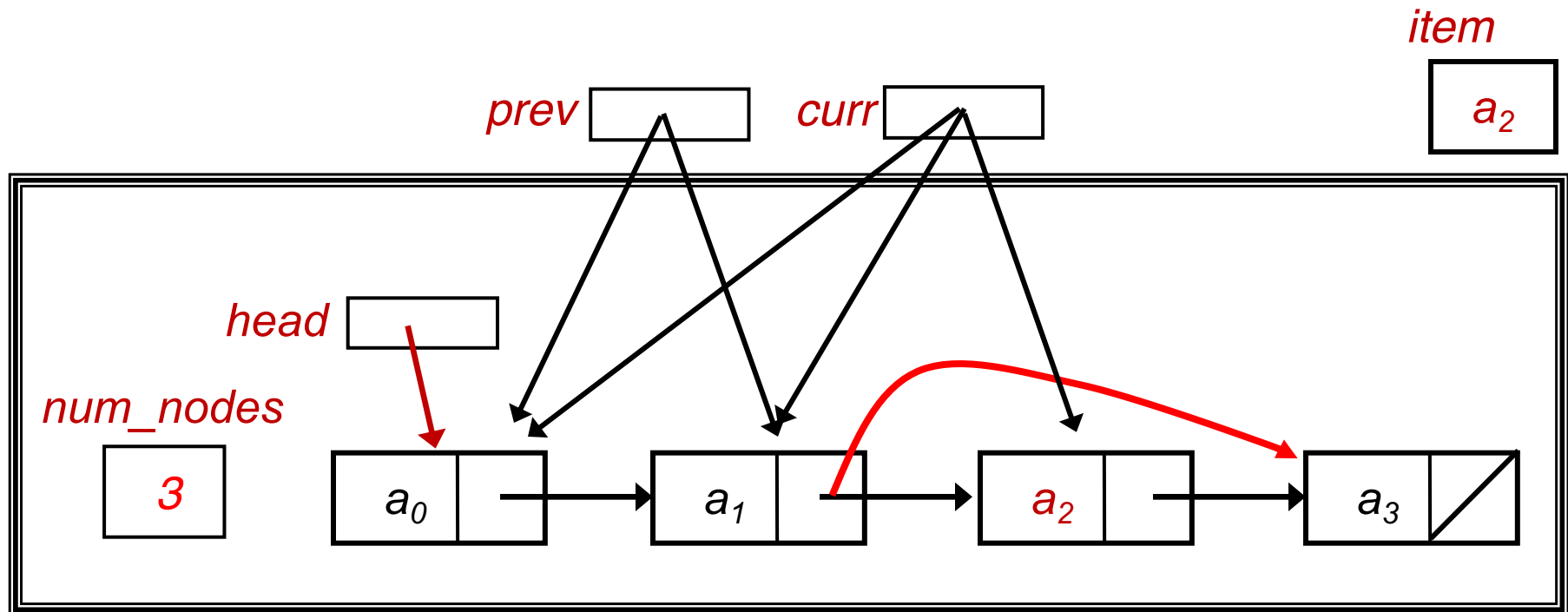
```
public E remove(E item)
    throws NoSuchElementException {
    // Write your code below...
    // Should make use of removeAfter() method.

}
}
```

EnhancedLinkedList.java

4.1 Enhanced Linked List (9/11)

```
public E remove(E item) throws ... {  
  
  
  
  
  
  
  
  
  
}
```



4.1 Test Enhanced Linked List (10/11)

```
import java.util.*;

public class TestEnhancedLinkedList {
    public static void main(String [] args) throws NoSuchElementException {

        EnhancedLinkedList <String> list = new EnhancedLinkedList
<String>();
        System.out.println("Part 1");
        list.addFirst("aaa");
        list.addFirst("bbb");
        list.addFirst("ccc");
        list.print();

        System.out.println();
        System.out.println("Part 2");
        ListNode <String> current = list.getHead();
        list.addAfter(current, "xxx");
        list.addAfter(current, "yyy");
        list.print();
    }
}
```

TestEnhancedLinkedList.java

4.1 Test Enhanced Linked List (11/11)

// (continue from previous slide)

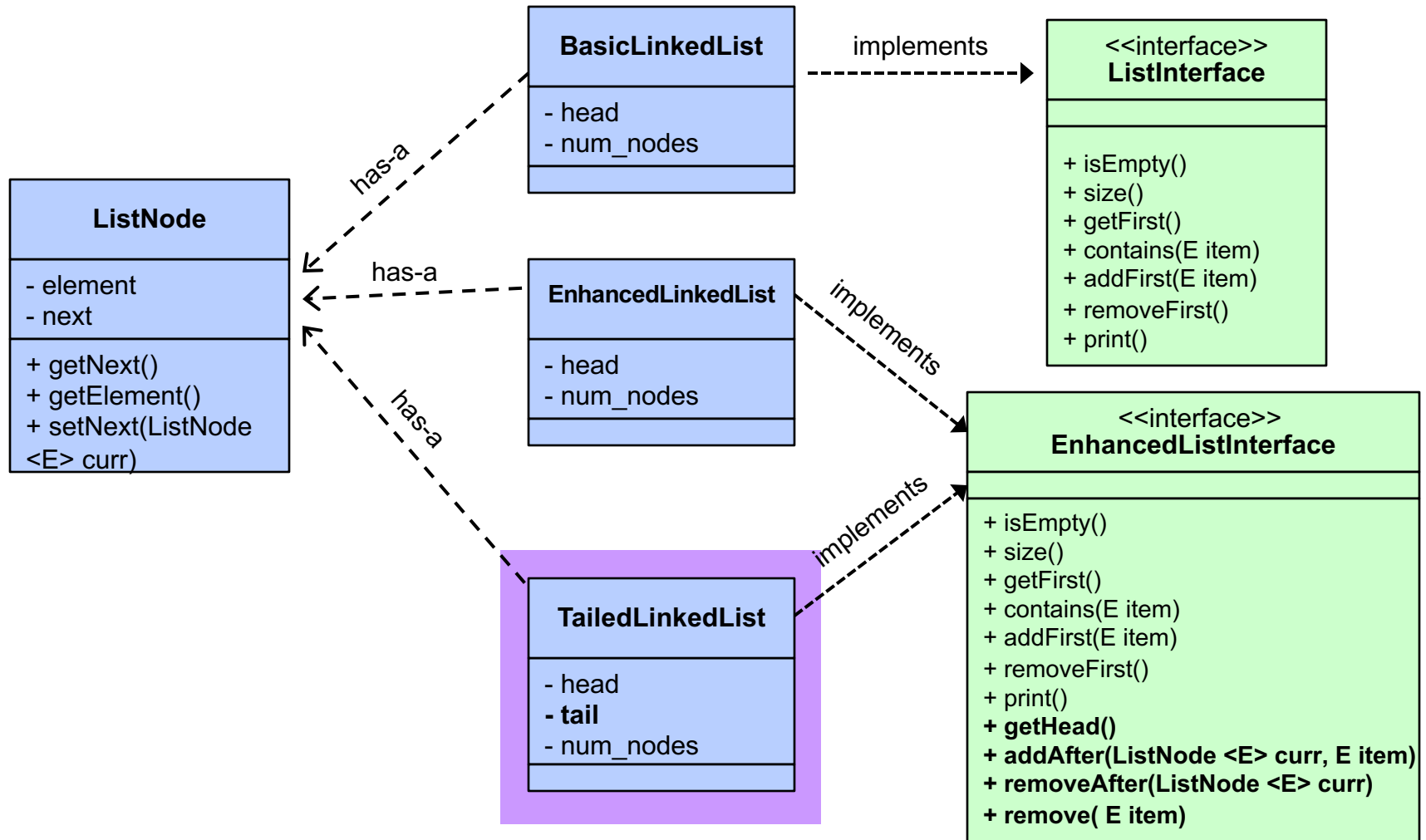
TestEnhancedLinkedList.java

```
System.out.println();
System.out.println("Part 3");
current = list.getHead();
if (current != null) {
    current = current.getNext();
    list.removeAfter(current);
}
list.print();

System.out.println();
System.out.println("Part 4");
list.removeAfter(null);
list.print();
}
}
```

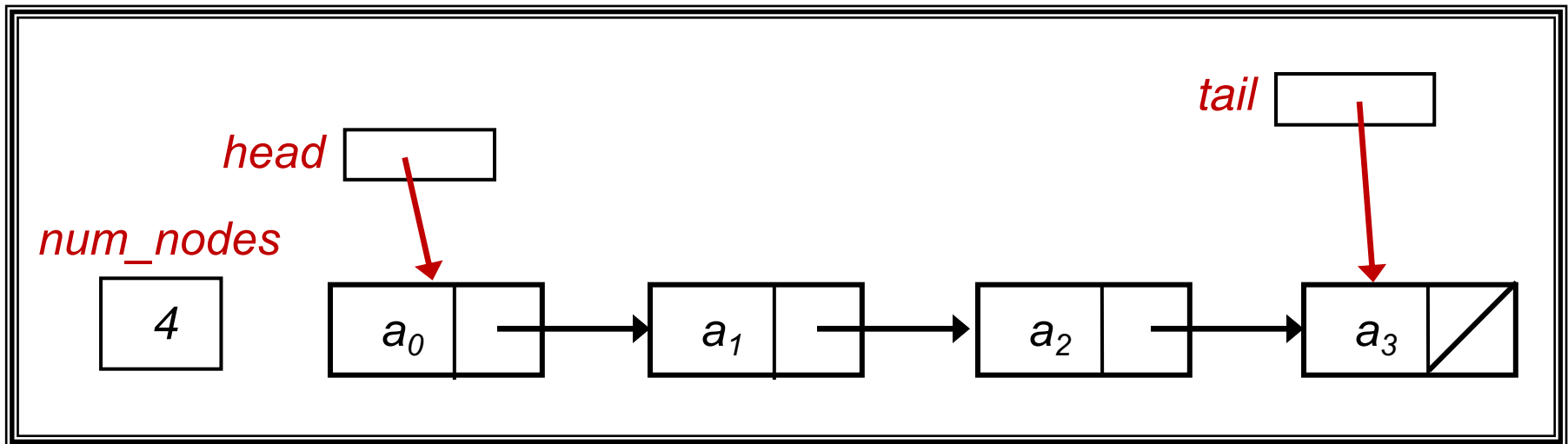
4. Linked Lists: Variants

OVERVIEW!



4.2 Tailed Linked List (1/10)

- We further improve on [Enhanced Linked List](#)
 - To address the issue that adding to the end is slow
 - Add an extra data member called **tail**
 - Extra data member means extra maintenance too – no free lunch!
 - (Note: We could have created this [Tailed Linked List](#) as a subclass of [Enhanced Linked List](#), but here we will create it from scratch.)
- Difficulty: Learn to take care of ALL cases of updating...



4.2 Tailed Linked List (2/10)

- A new data member: **tail**
- Extra maintenance needed, eg: see **addFirst()**

```
import java.util.*;
```

TailedLinkedList.java

```
class TailedLinkedList <E> implements EnhancedListInterface <E> {  
    private ListNode <E> head = null;  
    private ListNode <E> tail = null;  
    private int num_nodes = 0;  
  
    public ListNode <E> getTail() { return tail; }  
  
    public void addFirst(E item) {  
        head = new ListNode <E> (item, head);  
        num_nodes++;  
        if (num_nodes == 1)  
            tail = head;  
    }  
}
```

New code

4.2 Tailed Linked List (3/10)

- With the new member **tail**, can add to the end of the list directly by creating a new method **addLast()**
 - Remember to update **tail**

```
public void addLast(E item) {  
    if (head != null) {  
        tail.setNext(new ListNode <E> (item));  
        tail = tail.getNext();  
    } else {  
        tail = new ListNode <E> (item);  
        head = tail;  
    }  
    num_nodes++;  
}
```

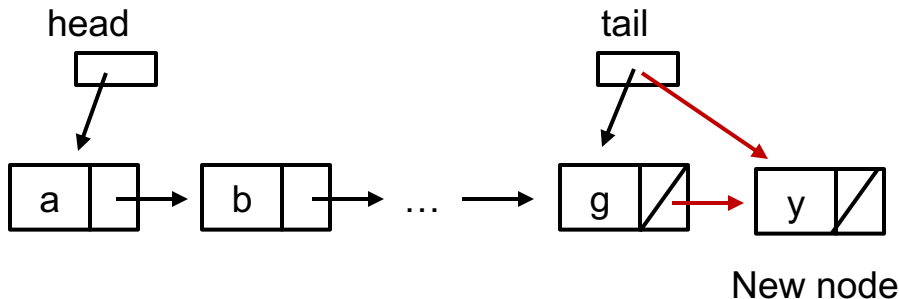
TailedLinkedList.java

4.2 Tailed Linked List (4/10)

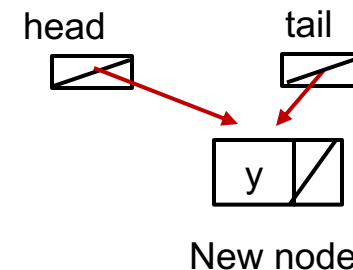
TailedLinkedList.java

```
public void addLast(E item) {  
    if (head != null) {  
        → tail.setNext(new ListNode <E> (item));  
        → tail = tail.getNext();  
    } else {  
        → tail = new ListNode <E> (item);  
        → head = tail;  
    }  
    num_nodes++;  
}
```

■ Case 1: head != null



■ Case 2: head == null



4.2 Tailed Linked List (5/10)

■ addAfter() method

TailedLinkedList.java

```
public void addAfter(ListNode <E> current, E item) {
    if (current != null) {
        current.setNext(new ListNode <E> (item, current.getNext()));
        if (current == tail)
            tail = current.getNext();
    } else { // add to the front of the list
        head = new ListNode <E> (item, head);
        if (tail == null)
            tail = head;
    }
    num_nodes++;
}
```

We may replace our earlier **addFirst()** method (in [slide 55](#)) with a simpler one that merely calls **addAfter()**. How?
Hint: Study the **removeFirst()** method ([slide 62](#)).

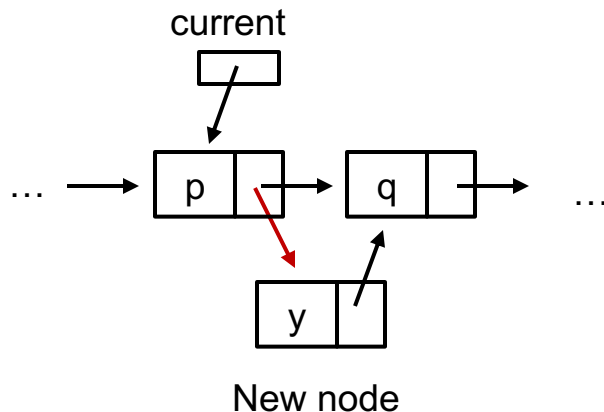
4.2 Tailed Linked List (6/10)

TailedLinkedList.java

```
public void addAfter(ListNode <E> current, E item) {  
    if (current != null) {  
        → current.setNext(new ListNode <E> (item, current.getNext()));  
        if (current == tail)  
            → tail = current.getNext();  
    } else {  
        . . .  
    }  
    num_nodes++;  
}
```

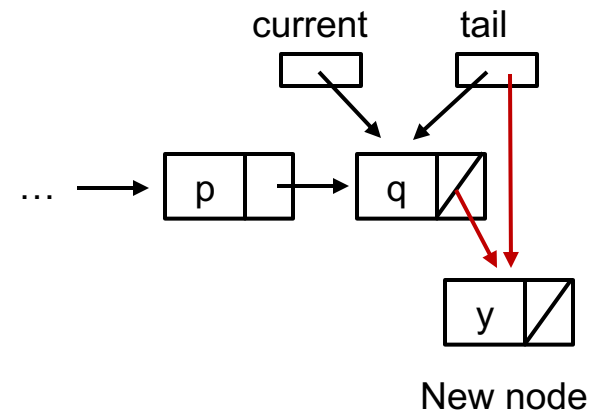
■ Case 1A

- current != null; current != tail



■ Case 1B

- current != null; current == tail



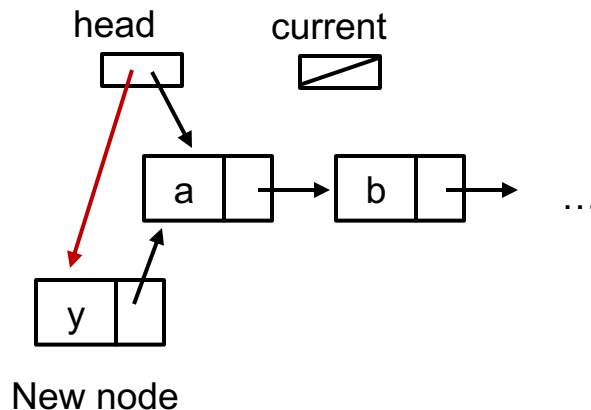
4.2 Tailed Linked List (7/10)

TailedLinkedList.java

```
public void addAfter(ListNode <E> current, E item) {  
    if (current != null) {  
        . . .  
    } else { // add to the front of the list  
→ head = new ListNode <E> (item, head);  
    if (tail == null)  
→ tail = head;  
    }  
    num_nodes++;  
}
```

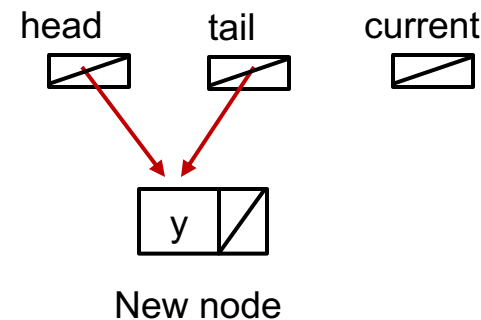
■ Case 2A

- current == null; tail != null



■ Case 2B

- current == null; tail == null



4.2 Tailed Linked List (8/10)

■ removeAfter() method

TailedLinkedList.java

```
public E removeAfter(ListNode <E> current)
    throws NoSuchElementException {
    E temp;
    if (current != null) {
        ListNode <E> nextPtr = current.getNext();
        if (nextPtr != null) {
            temp = nextPtr.getElement();
            current.setNext(nextPtr.getNext());
            num_nodes--;
            if (nextPtr.getNext() == null) // last node is removed
                tail = current;
            return temp;
        } else throw new NoSuchElementException("...");
    } else { // if current == null, we want to remove head
        if (head != null) {
            temp = head.getElement();
            head = head.getNext();
            num_nodes--;
            if (head == null) tail = null;
            return temp;
        } else throw new NoSuchElementException("...");
    }
}
```


4.2 Tailed Linked List (9/10)

- `removeFirst()` method
 - `removeFirst()` is a special case in `removeAfter()`

```
public E removeFirst() throws NoSuchElementException {  
    return removeAfter(null);  
}
```

TailedLinkedList.java

- Study the full program [TailedLinkedList.java](#) on the module website on your own.

4.2 Test Tailed Linked List (10/10)

TestTailedLinkedList.java

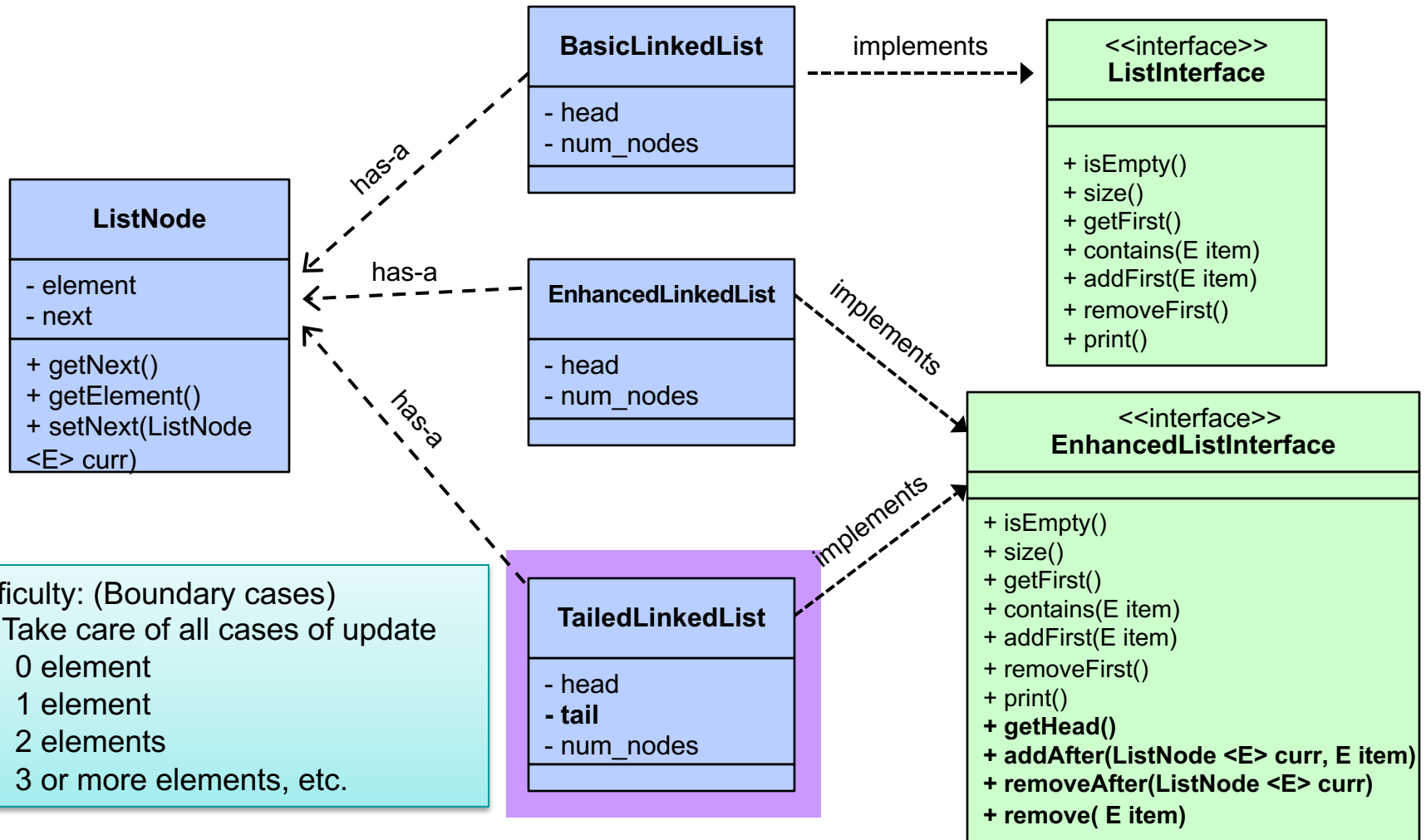
```
import java.util.*;

public class TestTailedLinkedList {
    public static void main(String [] args) throws NoSuchElementException {
        TailedLinkedList <String> list = new TailedLinkedList <String>();

        System.out.println("Part 1");
        list.addFirst("aaa");
        list.addFirst("bbb");
        list.addFirst("ccc");
        list.print();
        System.out.println("Part 2");
        list.addLast("xxx");
        list.print();
        System.out.println("Part 3");
        list.removeAfter(null);
        list.print();
    }
}
```

4. Linked Lists: Variants

OVERVIEW!





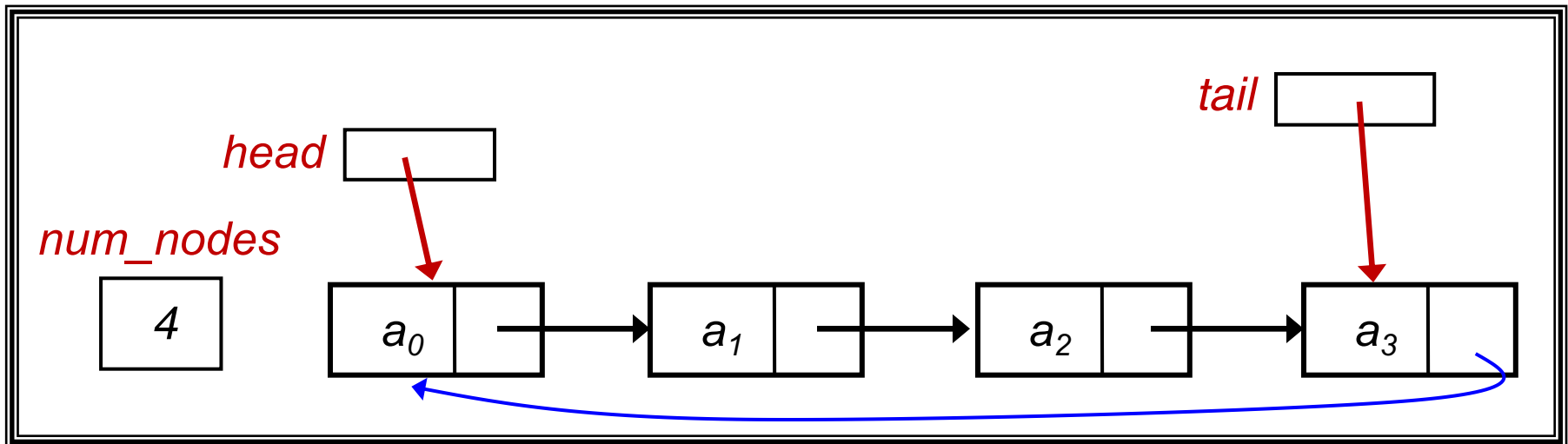
5 Other Variants

Other variants of linked lists

5.1 Circular Linked List



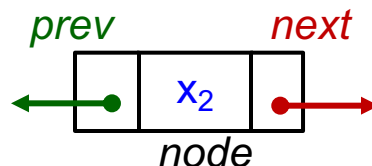
- There are many other possible enhancements of linked list
- Example: **Circular Linked List**
 - To allow cycling through the list repeatedly, e.g. in a **round robin system** to assign shared resource
 - Add a link from **tail** node of the TailedLinkedList to point back to **head** node
 - Different in linking need different maintenance – no free lunch!
- Difficulty: Learn to take care of ALL cases of updating, such as inserting/deleting the first/last node in a Circular Linked List
- Explore this on your own; write a class **CircularLinkedList**



5.2 Doubly Linked List (1/3)



- In the preceding discussion, we have a “**next**” pointer to move forward
- Often, we need to move backward as well
- Use a “**prev**” pointer to allow backward traversal
- Once again, no free lunch – need to maintain “**prev**” in all updating methods
- Instead of **ListNode** class, need to create a **DListNode** class that includes the additional “**prev**” pointer



5.2 Doubly Linked List: DListNode (2/3)



DListNode.java

```
class DListNode <E> {
    /* data attributes */
    private E element;
    private DListNode <E> prev;
    private DListNode <E> next;

    /* constructors */
    public DListNode(E item) { this(item, null, null); }
    public DListNode(E item, DListNode <E> p, DListNode <E> n) {
        element = item; prev = p; next = n;
    }

    /* get the prev DListNode */
    public DListNode <E> getPrev() { return this.prev; }
    /* get the next DListNode */
    public DListNode <E> getNext() { return this.next; }

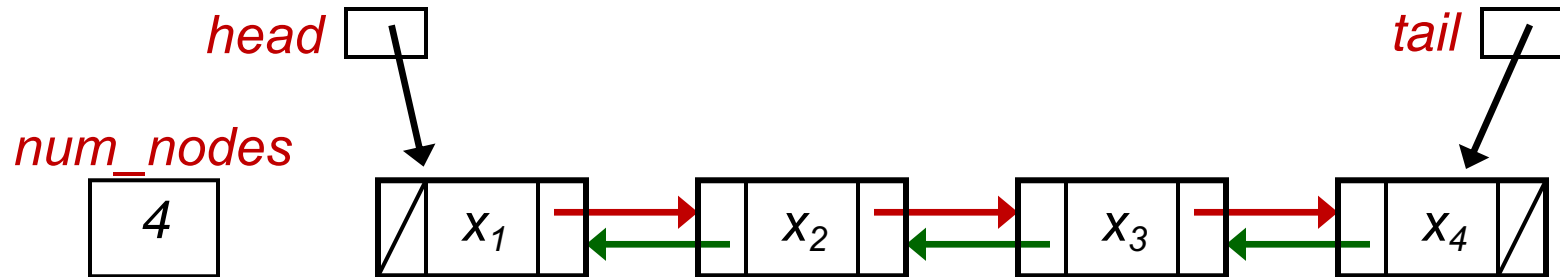
    /* get the element of the ListNode */
    public E getElement() { return this.element; }

    /* set the prev reference */
    public void setPrev(DListNode <E> p) { prev = p; }
    /* set the next reference */
    public void setNext(DListNode <E> n) { next = n; }
}
```

5.2 Doubly Linked List (3/3)



- An example of a doubly linked list



- Explore this on your own.
- Write a class `DoublyLinkedList` to implement the various linked list operations for a doubly linked list.

BÀI TẬP VỀ NHÀ

6 Java API: LinkedList class

Using the LinkedList class

6 Java Class: LinkedList <E>

- This is the class provided by Java library
- This is the linked list implementation of the List interface
- It has many more methods than what we have discussed so far of our versions of linked lists. On the other hand, we created some methods not available in the Java library class too.
- Please do not confuse this library class from our class illustrated here. In a way, we open up the Java library to show you the inside working.
- For purposes of sit-in labs or exam, please use whichever one as you are told if stated.

6.1 Class LinkedList: API (1/3)

Constructor Summary

[LinkedList\(\)](#)

Constructs an empty list.

[LinkedList\(Collection c\)](#)

Constructs a list containing the elements of the specified collection, in the order they are returned by the collection's iterator.

Method Summary

void [add](#)(int index, [Object](#) element)

Inserts the specified element at the specified position in this list.

boolean [add](#)([Object](#) o)

Appends the specified element to the end of this list.

boolean [addAll](#)([Collection](#) c)

Appends all of the elements in the specified collection to the end of this list, in the order that they are returned by the specified collection's iterator.

boolean [addAll](#)(int index, [Collection](#) c)

Inserts all of the elements in the specified collection into this list, starting at the specified position.

void [addFirst](#)([Object](#) o)

Inserts the given element at the beginning of this list.

void [addLast](#)([Object](#) o)

Appends the given element to the end of this list.

void [clear](#)()

Removes all of the elements from this list.

6.1 Class LinkedList: API (2/3)

<code>boolean</code>	<code>contains(Object o)</code> Returns true if this list contains the specified element.
<code>Object</code>	<code>get(int index)</code> Returns the element at the specified position in this list.
<code>Object</code>	<code>getFirst()</code> Returns the first element in this list.
<code>Object</code>	<code>getLast()</code> Returns the last element in this list.
<code>int</code>	<code>indexOf(Object o)</code> Returns the index in this list of the first occurrence of the specified element, or -1 if the List does not contain this element.
<code>int</code>	<code>lastIndexOf(Object o)</code> Returns the index in this list of the last occurrence of the specified element, or -1 if the list does not contain this element.
<code>ListIterator</code>	<code>listIterator(int index)</code> Returns a list-iterator of the elements in this list (in proper sequence), starting at the specified position in the list.
<code>Object</code>	<code>remove(int index)</code> Removes the element at the specified position in this list.
<code>boolean</code>	<code>remove(Object o)</code> Removes the first occurrence of the specified element in this list.
<code>Object</code>	<code>removeFirst()</code> Removes and returns the first element from this list.
<code>Object</code>	<code>removeLast()</code> Removes and returns the last element from this list.

6.1 Class LinkedList: API (3/3)

<u>Object</u>	<u>set</u> (int index, <u>Object</u> element) Replaces the element at the specified position in this list with the specified element.
int	<u>size</u> () Returns the number of elements in this list.
<u>Object</u> []	<u>toArray</u> () Returns an array containing all of the elements in this list in the correct order.
<u>Object</u> []	<u>toArray</u> (<u>Object</u> [] a) Returns an array containing all of the elements in this list in the correct order; the runtime type of the returned array is that of the specified array.

Methods inherited from class java.util.AbstractSequentialList

iterator

Methods inherited from class java.util.AbstractList

equals, hashCode, listIterator, removeRange, subList

Methods inherited from class java.util.AbstractCollection

containsAll, isEmpty, removeAll, retainAll, toString

Methods inherited from class java.lang.Object

finalize, getClass, notify, notifyAll, wait, wait, wait

Methods inherited from interface java.util.List

containsAll, equals, hashCode, isEmpty, iterator, listIterator, removeAll, retainAll, subList

6.2 Class LinkedList (1/2)

- An example use (Page 1 of 2)

TestLinkedListAPI.java

```
import java.util.*;

public class TestLinkedListAPI {

    static void printList(LinkedList <Integer> alist) {
        System.out.print("List is: ");
        for (int i = 0; i < alist.size(); i++)
            System.out.print(alist.get(i) + "\t");
        System.out.println();
    }

    // Print elements in the list and also delete them
    static void printListv2(LinkedList <Integer> alist) {
        System.out.print("List is: ");
        while (alist.size() != 0) {
            System.out.print(alist.element() + "\t");
            alist.removeFirst();
        }
        System.out.println();
    }
}
```

6.2 Class LinkedList (2/2)

- An example use (Page 2 of 2)

TestLinkedListAPI.java

```
public static void main(String [] args) {  
    LinkedList <Integer> alist = new LinkedList <Integer> ();  
    for (int i = 1; i <= 5; i++)  
        alist.add(new Integer(i));  
  
    printList(alist);  
  
    System.out.println("First element: " + alist.getFirst());  
    System.out.println("Last element: " + alist.getLast());  
  
    alist.addFirst(888);  
    alist.addLast(999);  
    printListv2(alist);  
    printList(alist);  
}  
}
```


Why “reinvent the wheel”?

- In a data structures course, students are often asked to implement well-known data structures.
- A question we sometimes hear from students: “Since there is the API, why do we need to learn to write our own code to implement a data structure like linked list?”
- Writing the code allows you to gain an indepth understanding of the data structures and their operations
- The understanding will allow you to appreciate their complexity analysis (to be covered later) and use the API effectively

7 Summary (1/2)

- We learn to create our own data structure
 - In creating our own data structure, we face 3 difficulties:
 1. **Re-use of codes** (inheritance confusion)
 2. Manipulation of **pointers/references** (The sequence of statements is important! With the wrong sequence, the result will be wrong.)
 3. Careful with all the **boundary cases**
 - Drawings are very helpful in understanding the cases (point 3), which then can help in knowing what can be used/manipulated (points 1 and 2)

7 Summary (2/2)

- Once we can get through this lecture, the rest should be smooth sailing as all the rest are similar in nature
 - You should try to add more methods to our versions of `LinkedList`, or to extend `ListNode` to other type of node
- Please do not forget that the Java Library class is much more comprehensive than our own – for sit-in labs and exam, please use whichever one as you are told if stated.

9 Visualising Data Structures

- See <http://visualgo.net>
 - Click on “Linked List, Stack, Queue”
 - (Non-linear data structures such as trees and graphs will be covered in 502043.)
- See <http://www.cs.usfca.edu/~galles/visualization/Algorithms.html>

End of file