

Arrays and Linked Lists

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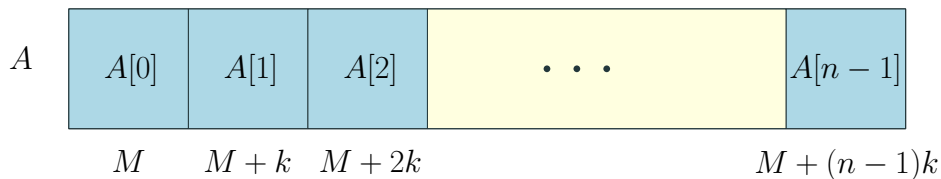
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What is an array?

Definition

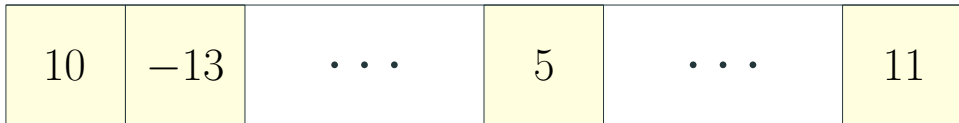
An array is a **contiguous** sequence of memory locations each of which can hold items of a fixed data type



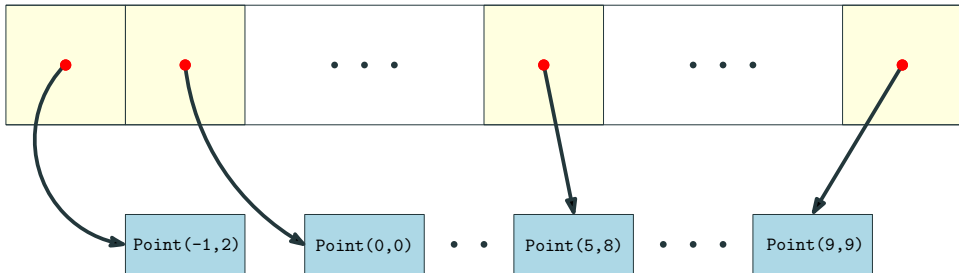
Your first data structure!

Arrays of primitives vs Arrays of objects

An array of primitives



An array of objects



How to create an array of **objects**?

- **Approach 1.** declaring and defining the array at the same time.

```
Point[] anArrayOfPoints = {new Point(1.1,2.1), new Point(3.1, 4.1), new Point(5.1,6.1)};
```

- **Approach 2.** allocate the array and then create the objects.

```
Point[] anArrayOfPoints = new Point[n]; // point objects are not created yet!  
// double x = anArrayOfPoints[5].getX(); <-- cannot use this; objects are not created yet; will throw a NullPointerException  
for(int i = 0; i < anArrayOfPoints.length; i++)  
    anArrayOfPoints[i] = new Point(Math.random() * 10, Math.random() * 10);
```

Deep copy vs shallow copy

Shallow copy: source and destination point to the same entities

```
int[] sourceArrayA = {10,20,30,40,50};  
int[] destinationArrayA = sourceArrayA; // shallow-copy; just copying references; both point to the same array in the memory
```

Deep copy: source and destination point to different entities

```
int[] sourceArrayB = {50,60,70,80,90,100};  
int[] destinationArrayB = new int[sourceArrayB.length];  
  
for(int index = 0; index < sourceArrayB.length; index++) //deep-copy; copying stuff to the destination array  
    destinationArrayB[index] = sourceArrayB[index];  
  
// Another way to deep copy in Java  
int[] sourceArrayC = {11,21,31,41,51};  
int[] destinationArrayC = sourceArrayC.clone(); // deep-copy; beware! shallow-copy for non-primitives
```

Let us look at a demo
Class name. **CopyingDemo**

A few things about arrays

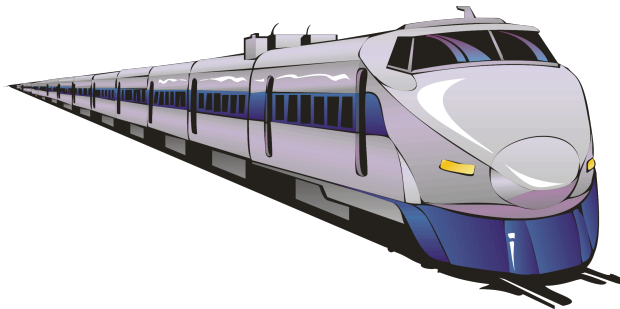
Good things

- Fast accesses for reading and writing since every location is indexed; every access takes $O(1)$ time (constant time)
- Once an array is allocated no more memory allocation worries!
- Super-simple coding (`arr[i] = 10; a[i] = b[j] + c[k]; x = t[i]; etc.`)

Bad things

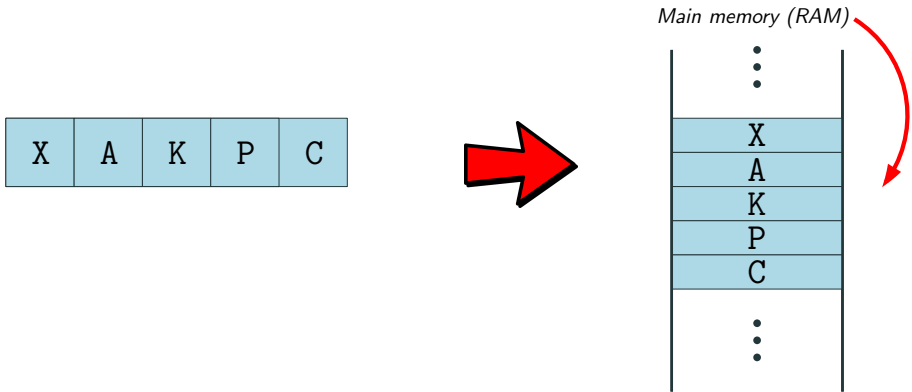
- Need to know array-size in advance otherwise, an array may run out of space for holding the incoming items; on the other hand, if too much of extra space is allocated in advance, space may remain unused (*bad memory utilization*)
- Cannot grow (arrays are **static**)
- Insertions/deletions can be expensive since right/left shifts are required which take $O(n)$ time in the worst case

The solution



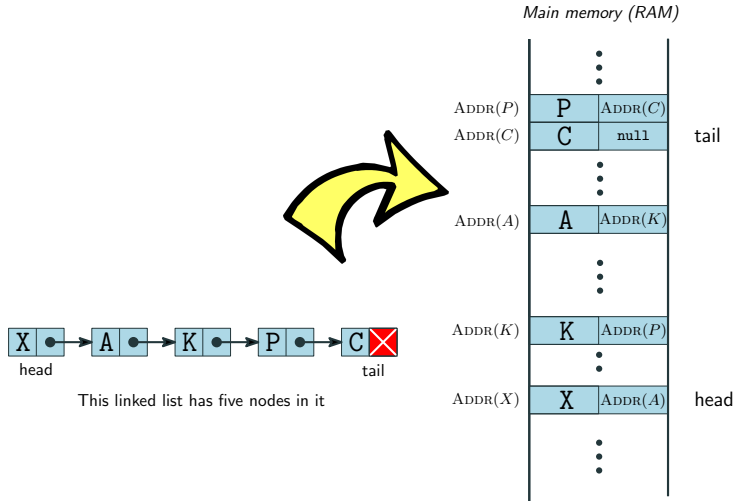
Linked Lists (Singly/Doubly/Circular)
Our first *dynamic* data structure

Layouts of arrays



Layout of arrays in the main memory (RAM)

Linked lists: what are they?



Layout of **singly** linked lists in the main memory (RAM)

Coding the example (a very naive way of course!)

```
public class ToySinglyLinkedList {  
  
    public static class Node { // a nested node  
        Character element;  
        Node next;  
  
        public Node(Character element, Node next) {  
            this.element = element;  
            this.next = next;  
        }  
  
        public void setNext(Node next) {  
            this.next = next;  
        }  
  
        public Character getElement() {  
            return element;  
        }  
    }  
}  
  
// contd. on the next slide
```

Coding the example (a very naive way of course!)

```
public class ToySinglyLinkedList {  
    // contd. from the previous slide  
    public static void main(String[] args) {  
        Node nodeX = new Node('X',null);  
        Node nodeA = new Node('A',null);   nodeX.setNext(nodeA);  
        Node nodeK = new Node('K',null);   nodeA.setNext(nodeK);  
        Node nodeP = new Node('P',null);   nodeK.setNext(nodeP);  
        Node nodeC = new Node('C',null);   nodeP.setNext(nodeC);  
  
        Node current = nodeX;  
        while( current != null ) {  
            System.out.print(current.getElement());  
  
            if(current.next != null)  
                System.out.print(" -> ");  
  
            current = current.next;  
        }  
    }  
}
```

Output

X -> A -> K -> P -> C

Good things about linked lists

- No need to worry about length in advance
- Can be grown/shrunk by manipulating the links and adding/deleting nodes (linked lists are **dynamic**)

👉 You **cannot** jump to a node directly like arrays! We need to traverse the list starting at the head using a for loop or a while loop and reach that node

👉 Coding can get a bit challenging at times.
NullPointerException is a common thing

It is time to go for generics!

**public class SinglyLinkedList<E> implements
Iterable<E>**

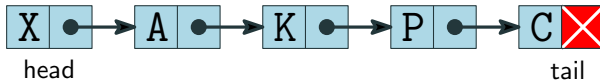
- ① **int** size() {...}
- ② **boolean** isEmpty() {...}
- ③ **E** first() {...}
- ④ **E** last() {...}
- ⑤ **void** addFirst(**E** e) {...}
- ⑥ **void** addLast(**E** e) {...}
- ⑦ **E** removeFirst() {...}
- ⑧ **boolean** addAfter(**E** predecessor, **E** incomingItem) {...}
- ⑨ **String** toString() {...}
- ⑩ **Iterator<E>** iterator() {...}

Adding a new node after a node: addAfter('K', 'T')

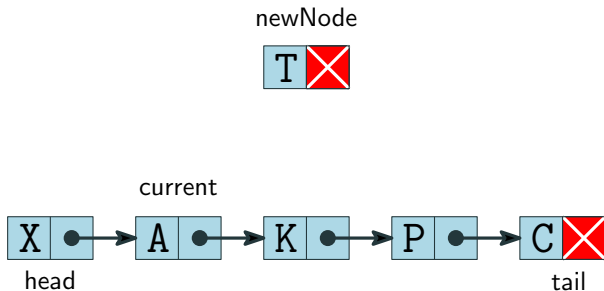
newNode



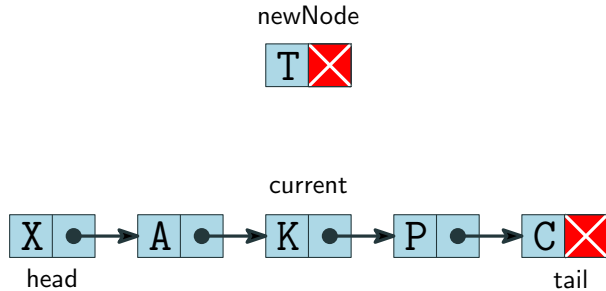
current



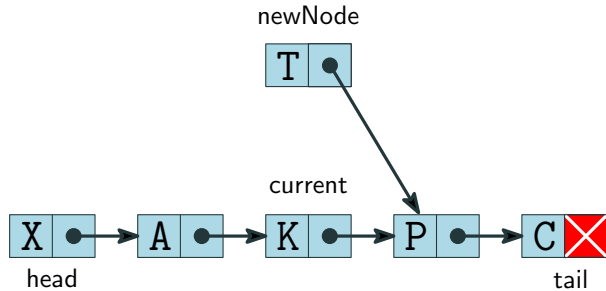
Adding a new node after a node: addAfter('K', 'T')



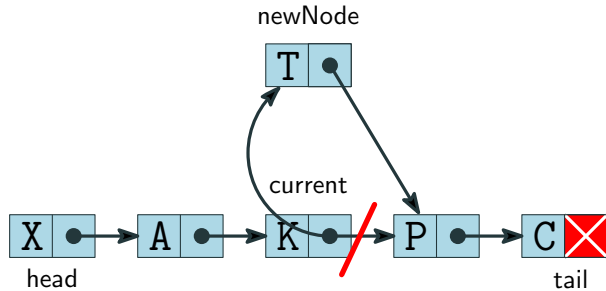
Adding a new node after a node: addAfter('K', 'T')



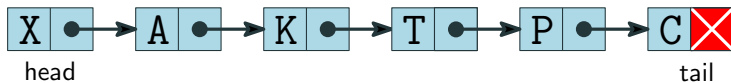
Adding a new node after a node: addAfter('K', 'T')



Adding a new node after a node: addAfter('K', 'T')



Adding a new node after a node: `addAfter('K', 'T')`



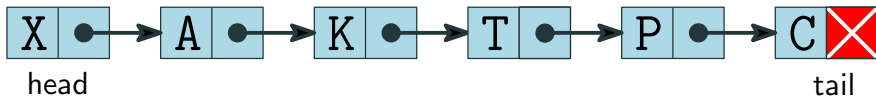
Complexity stuff

☞ Linked list traversals take $O(n)$ time

SinglyLinkedList<E>

- ① `int size() {...}`, **Time complexity:** $O(1)$
- ② `boolean isEmpty() {...}`, **Time complexity:** $O(1)$
- ③ `E first() {...}`, **Time complexity:** $O(1)$
- ④ `E last() {...}`, **Time complexity:** $O(1)$
- ⑤ `void addFirst(E e) {...}`, **Time complexity:** $O(1)$
- ⑥ `void addLast(E e) {...}`, **Time complexity:** $O(1)$
- ⑦ `E removeFirst() {...}`, **Time complexity:** $O(1)$
- ⑧ `boolean addAfter(E predecessor, E incomingItem) {...}`,
Time complexity: $O(n)$ where n is the number of nodes in the list currently
- ⑨ `String toString() {...}`, **Time complexity:** $O(n)$ where n is the number of nodes in the list currently

Limitations of singly linked lists



- Given just a reference to a node, we **cannot** efficiently delete it or add a node before it
- **Cannot** traverse from right to left just by following the links, if needed

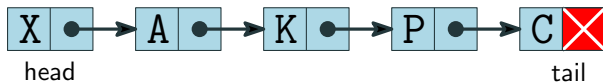
Solution

Store two links at every node: **prev** and **next**

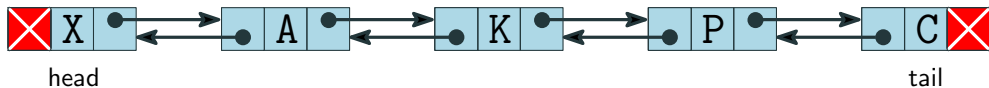
Downside?

Use of extra space at every node and possibly more complicated code

Doubly linked lists



A **singly** linked list

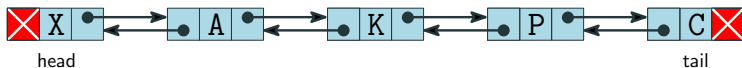


A **doubly** linked list

**public class DoublyLinkedList<E> implements
Iterable<E>**

- ① **int** size() {...}
- ② **boolean** isEmpty() {...}
- ③ **E** first() {...}
- ④ **E** last() {...}
- ⑤ **void** addBetween(**E** e, **Node<E>** predecessor, **Node<E>** successor) {...}
- ⑥ **E** remove(**Node<E>** node) {...}
- ⑦ **void** addFirst(**E** e) {...}
- ⑧ **void** addLast(**E** e) {...}
- ⑨ **E** removeFirst() {...}
- ⑩ **E** removeLast() {...}
- ⑪ **String** toString() {...}
- ⑫ **Iterator<E>** iterator() {...}

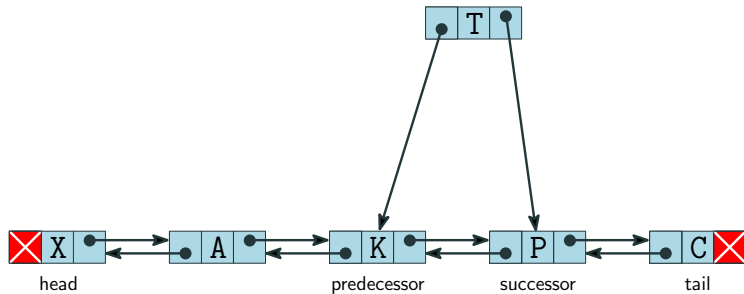
Illustrating addBetween(E e, Node<E> predecessor, Node<E> successor)



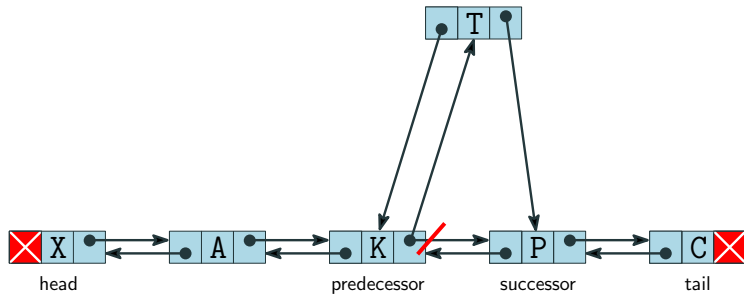
Illustrating addBetween(E e, Node<E> predecessor, Node<E> successor)



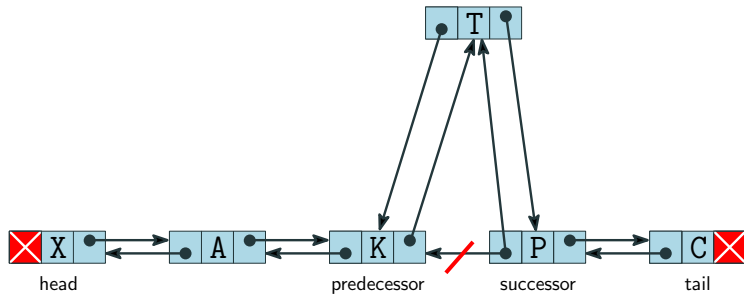
Illustrating addBetween(E e, Node<E> predecessor, Node<E> successor)



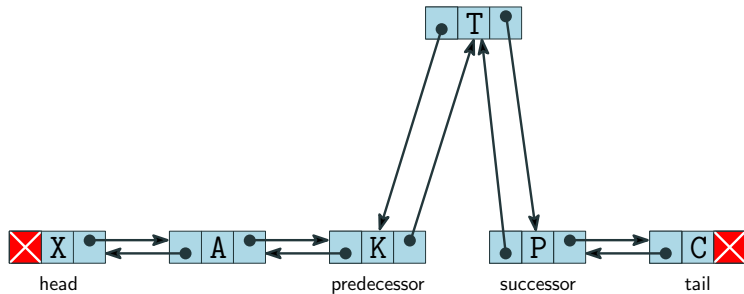
Illustrating addBetween(E e, Node<E> predecessor, Node<E> successor)



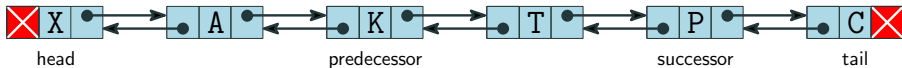
Illustrating addBetween(E e, Node<E> predecessor, Node<E> successor)



Illustrating addBetween(E e, Node<E> predecessor, Node<E> successor)



Illustrating addBetween(E e, Node<E> predecessor, Node<E> successor)



Complexity stuff

DoublyLinkedList<E>

- ① `int size() {...}`, **Time complexity:** $O(1)$
- ② `boolean isEmpty() {...}`, **Time complexity:** $O(1)$
- ③ `E first() {...}`, **Time complexity:** $O(1)$
- ④ `E last() {...}`, **Time complexity:** $O(1)$
- ⑤ `void addBetween(E e, Node<E> predecessor, Node<E> successor) {...}`
Time complexity: $O(1)$
- ⑥ `E remove(Node<E> node) {...}`, **Time complexity:** $O(1)$
- ⑦ `void addFirst(E e) {...}`, **Time complexity:** $O(1)$
- ⑧ `void addLast(E e) {...}`, **Time complexity:** $O(1)$
- ⑨ `E removeFirst() {...}`, **Time complexity:** $O(1)$
- ⑩ `E removeLast() {...}`, **Time complexity:** $O(1)$
- ⑪ `String toString() {...}`, **Time complexity:** $O(n)$ where n is the number of nodes in the list currently

For most linked list methods, traversing is required
Two popular approaches for traversing a linked list

Option A: while loop

```
Node<E> current = head;  
while( current != null ) {  
    // do something  
    current = current.next;  
}
```

Option B: for loop

```
Node<E> current = head;  
for(int pos = 0; pos < size; pos++) {  
    // do something  
    current = current.next;  
}
```


SLLs vs ArrayLists



- Linked lists can take substantially more space per data element compared to arrays and ArrayLists since every node is storing at least one link (reference to another node in the same list)
- Linked lists are slower than ArrayLists, especially when trying to execute many insertions at a go; every time an insertion is made, a memory allocation request has to be made for the new node. Further, more primitive operations need to be executed in the case of a linked list.

SLLs vs ArrayLists

```
Random generator = new Random();

SinglyLinkedList<Integer> LL = new SinglyLinkedList<>();

int n = 1000000;

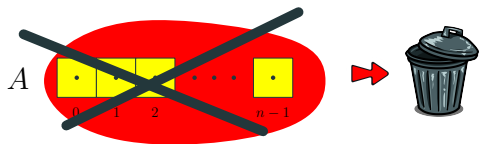
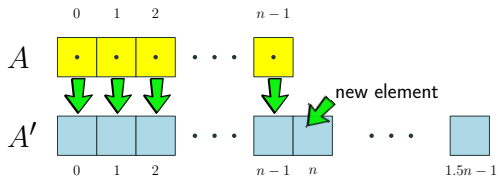
long startA = System.currentTimeMillis();
for(int i = 0; i < n; i++) {
    Integer randomInteger = generator.nextInt();
    LL.addLast(randomInteger);
}
long timeTakenA = System.currentTimeMillis() - startA;
System.out.println("Time taken by SLL: " + timeTakenA + " ms" ); // printed 162 ms in some run

ArrayList<Integer> AL = new ArrayList<>();

long startB = System.currentTimeMillis();
for(int i = 0; i < n; i++) {
    Integer randomInteger = generator.nextInt();
    AL.add(randomInteger);
}
long timeTakenB = System.currentTimeMillis() - startB;
System.out.println("Time taken by AL: " + timeTakenB + " ms" ); // printed 34 ms in the same run
```

So what is so special about ArrayLists?

- They are **dynamic** arrays (can insert/delete elements) and are maintained using plain arrays
- If there is no space for inserting a new element, a new array A' is created whose length is 1.5 times that of the current array A ; the elements in A are copied to A' and then the new incoming element is inserted at the first available spot from the left. Finally, A is deleted and A' becomes the new A .



- It means that we seldom need to allocate new memory since often empty cells are available for insertion at the end of the array.
- ArrayLists are thus fast and we also get indexing support!

How many times new array allocations are needed?

n (upto)	Array reallocations required
10	0
100	6
1,000	12
10,000	18
100,000	23
1,000,000	29
10,000,000	35

Initial array size is assume to be 10

👉 Even for inserting up to $10M$ elements, at most 35 reallocations are needed!

👉 See the class [COP3530ArrayList](#) for an implementation

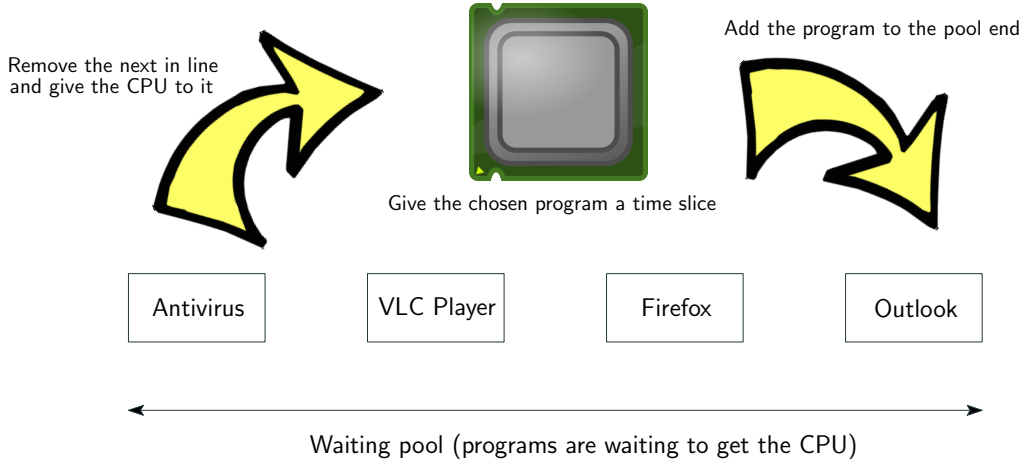
Why is the `StringBuilder` class so much faster than `String` class?

- **StringBuilder** is implemented as **dynamic array** and its objects are **mutable**
- In this case, **mutable** means if space is available, new items can be inserted
- Recall that dynamic arrays are very fast when we need to append a large number of times; that's why `StringBuilder` beats `String` when it comes to a appending a large number of characters
- On the other hand, **String** objects are **immutable** and every time a new append is executed, the existing `String` object is discarded and a new one is created *without increasing the new array capacity by a multiplicative factor*. Of course, the old content is transferred to the new object. Therefore, for n appends, approximately, n reallocations are needed.
- Such a large number of reallocations (approximately, n) drastically slows down `String` appends in practice!

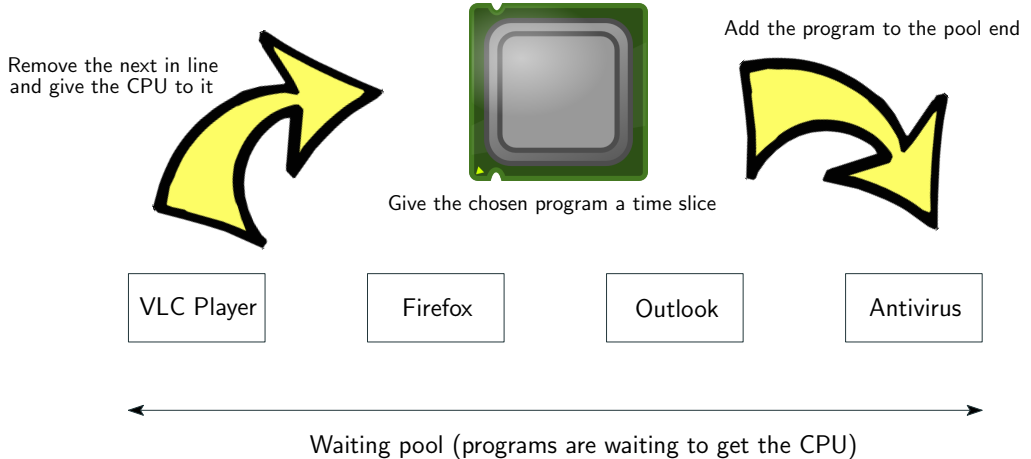
Maintaining a cyclic order

- In some applications we need the following two features:
 - ① Lists should be **dynamic**
 - ② Lists should have a **cyclic order**: well-defined neighboring relationships but no fixed beginning or end
- Example: maintain a cyclic list of processes (programs in execution) which need CPU access in the cyclic order (this is known as **round-robin scheduling** in the operating system literature)

Example

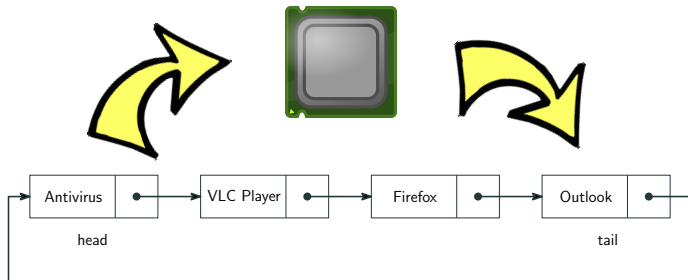


Example

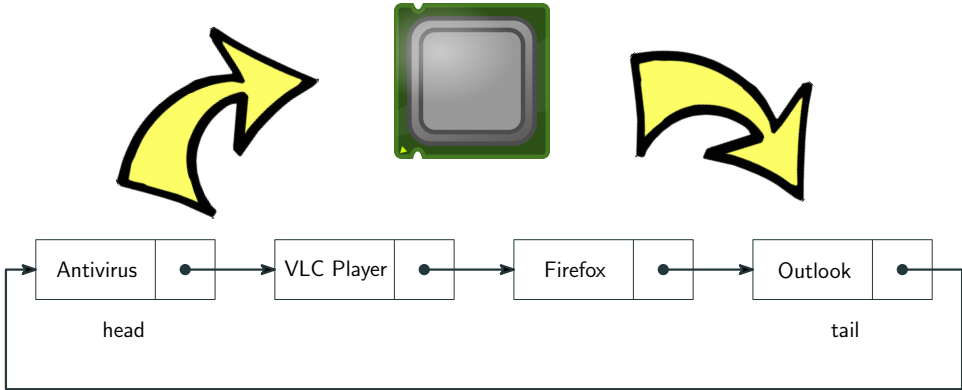


Circular linked list

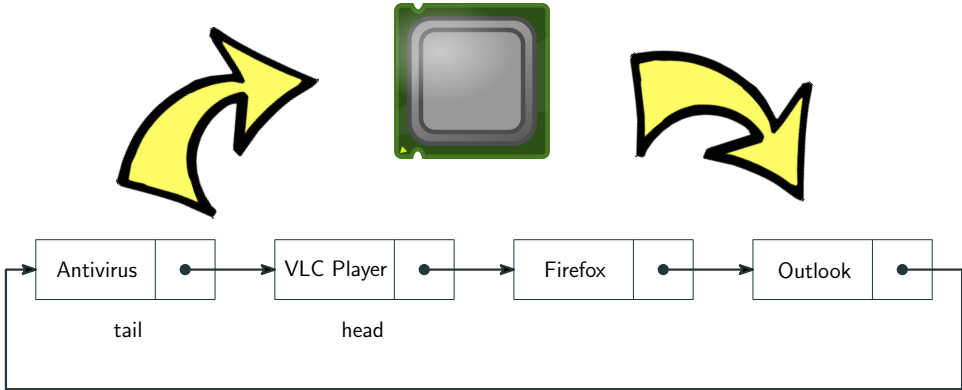
Idea! make the tail point to the head



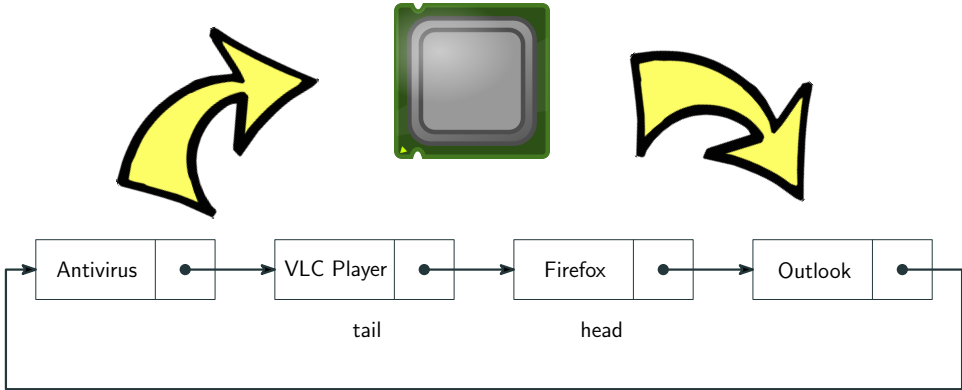
Circular linked list



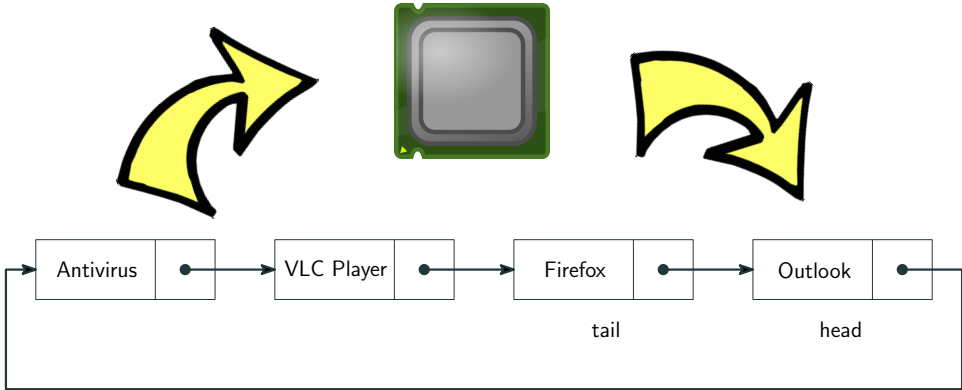
Circular linked list



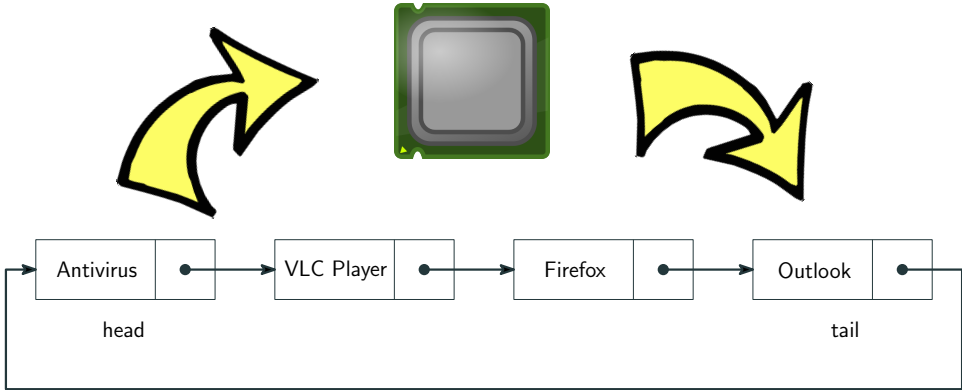
Circular linked list



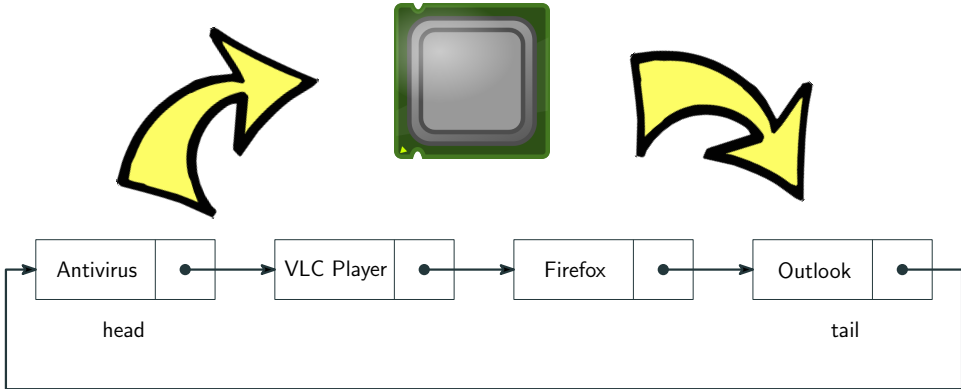
Circular linked list



Circular linked list



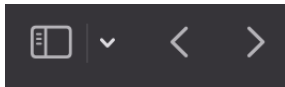
Advantage?



**public class CircularLinkedList<E> implements
Iterable<E>**

- ① **int** size() {...}, **Time complexity:** $O(1)$
- ② **boolean** isEmpty() {...}, **Time complexity:** $O(1)$
- ③ **E** first() {...}, **Time complexity:** $O(1)$
- ④ **E** last() {...}, **Time complexity:** $O(1)$
- ⑤ **void** rotate() {...}, **Time complexity:** $O(1)$
- ⑥ **void** addFirst(E e) {...}, **Time complexity:** $O(1)$
- ⑦ **void** addLast(E e) {...}, **Time complexity:** $O(1)$
- ⑧ **E** removeFirst() {...}, **Time complexity:** $O(1)$
- ⑨ **Iterator<E>** iterator() {...}

Browser tabs: an application of linked lists



- For every tab, we get to see the *go forward* and *go backward* buttons
- How to implement this button
- Use 2 linked lists: one for the *go backward* button and one for the *go forward* button

Code

```
public class BrowserTab {
    String currentPage = "";
    private final DoublyLinkedList<String> previousPages = new DoublyLinkedList<>(), nextPages = new DoublyLinkedList<>();

    public static String getTimeStamp(){ return "[" + new Date() + "] "; }

    public BrowserTab() { System.out.println(getTimeStamp() + "New tab opened."); }

    public void typeAndGoNewSite(String newPage) {
        if( !currentPage.isEmpty() ) previousPages.addLast(currentPage);
        currentPage = newPage;
        System.out.println(getTimeStamp() + "Currently viewing: " + currentlyViewing());
    }

    // contd. on the next slide
}
```

Code

```
public class BrowserTab {
    public void clickOnGoBackButton() {
        if( previousPages.isEmpty() ) {
            System.out.println(getTimeStamp() + "Back button is greyed out (unavailable).");
            return;
        }
        else {
            nextPages.addFirst(currentPage);
            currentPage = previousPages.last();
            previousPages.removeLast();
        }
        System.out.println(getTimeStamp() + "Currently viewing: " + currentlyViewing());
    }
    public void clickOnGoForward() {
        if( nextPages.isEmpty() ) {
            System.out.println(getTimeStamp() + "Forward button is greyed out (unavailable).");
            return;
        }
        else {
            previousPages.addLast(currentPage);
            currentPage = nextPages.removeFirst();
        }
        System.out.println(getTimeStamp() + "Currently viewing: " + currentlyViewing());
    }
    // contd. on the next slide
}
```

Code

```
public class BrowserTab {  
  
    public String currentlyViewing() { return currentPage; }  
  
    public String toString() {  
        StringBuilder prettyString = new StringBuilder();  
  
        for (String site : previousPages)  
            prettyString.append(site).append(" ");  
  
        prettyString.append(" ***").append(currentPage).append(" *** ");  
  
        for (String site : nextPages)  
            prettyString.append(site).append(" ");  
  
        return prettyString.toString();  
    }  
}
```

For an usage refer to the class **SimulateGodzillaHigherFox**

Chapter 5 from

<https://opensa-server.cs.vt.edu/OpenDSA/Books/CS3/html/>