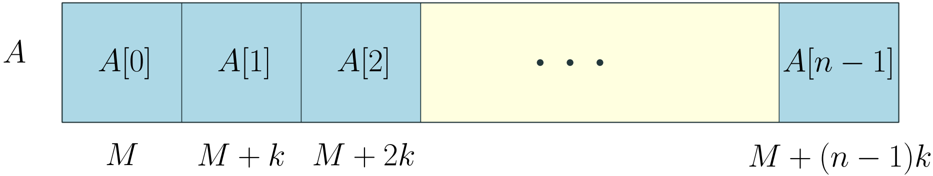
Arrays and Linked Lists

Dr. Anirban Ghosh

School of Computing
University of North Florida

Definition

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



M is the memory address of $A[0]$ and k is the space occupied by an array cell

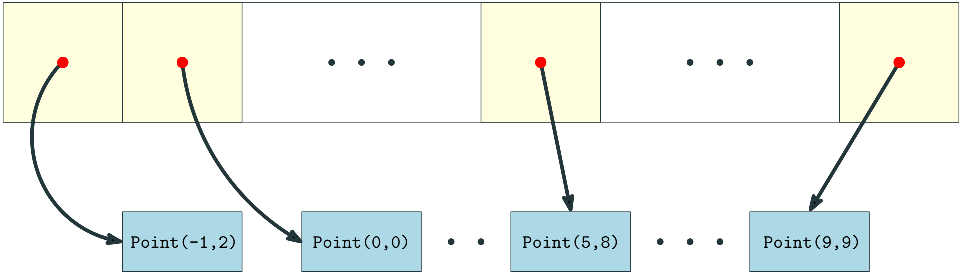
Your first data structure!

Arrays of primitives vs Arrays of objects

An array of **primitives**

10	-13	$\cdots$	5	$\cdots$	11

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

```java
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

```java
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`

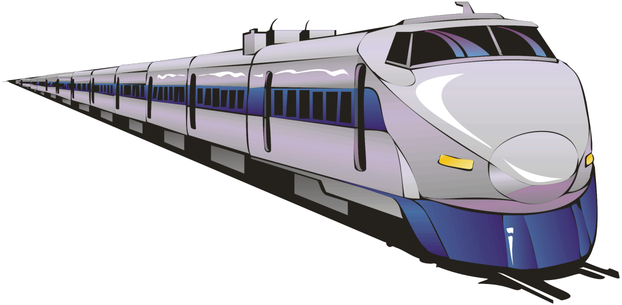
A few things about arrays

Good things

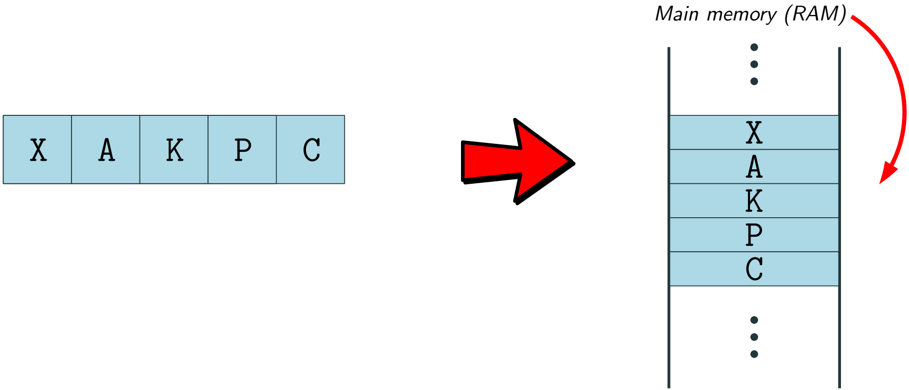
- Fast accesses for reading and writing since every location is indexed; every access takes $O(1)$ time (constant time)
- Once an array is allocated no more memory allocation worries!
- Super-simple coding (`arr[i] = 10; a[i] = b[j] + c[k]; x = t[i]; etc.`)

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

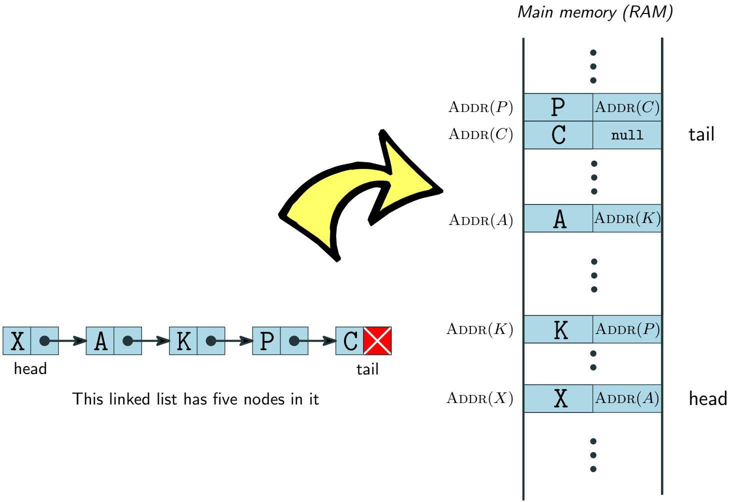


Linked Lists (Singly/Doubly/Circular)
Our first dynamic data structure



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!)

```java
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!)

```java
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

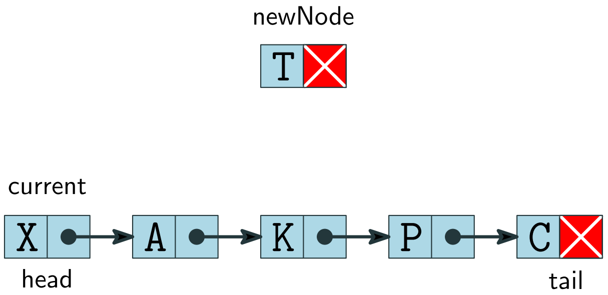
☞ Coding can get a bit challenging at times. **`NullPointerException`** is a common thing

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')`



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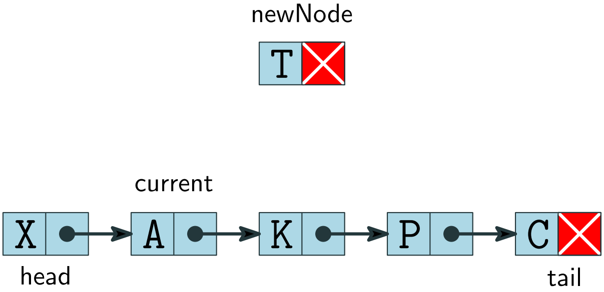

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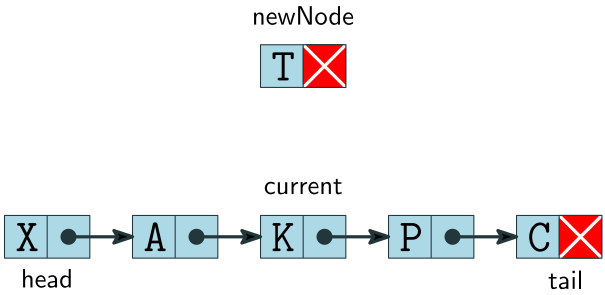
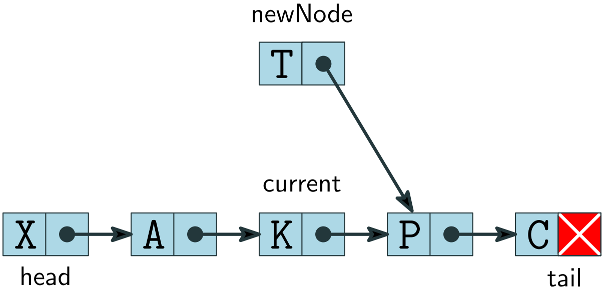
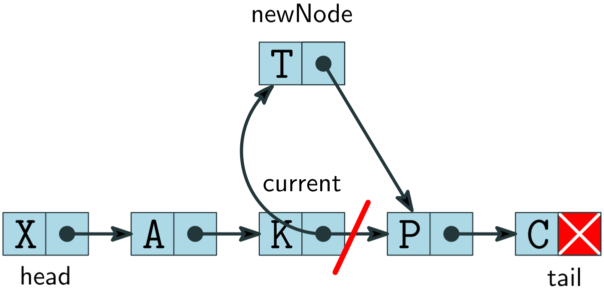


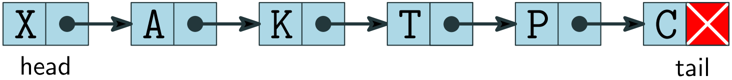
Adding a new node after a node: `addAfter('K','T')`



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



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



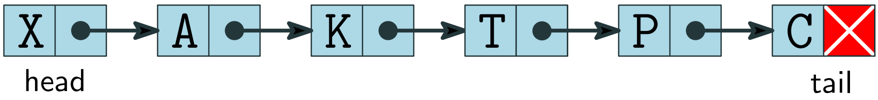
Complexity stuff

☞ 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



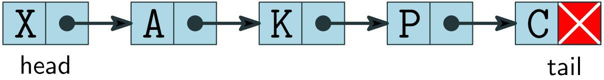
- Given just a reference to a node, we **cannot** efficiently delete it or add a node before it
- **Cannot** traverse from right to left just by following the links, if needed

Solution

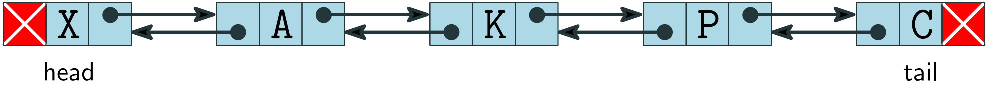
Store two links at every node: **prev** and **next**

Downside?

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



A **singly** linked list



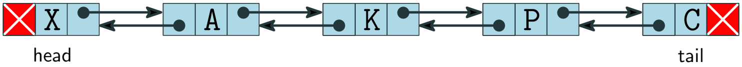
A **doubly** linked list

Methods

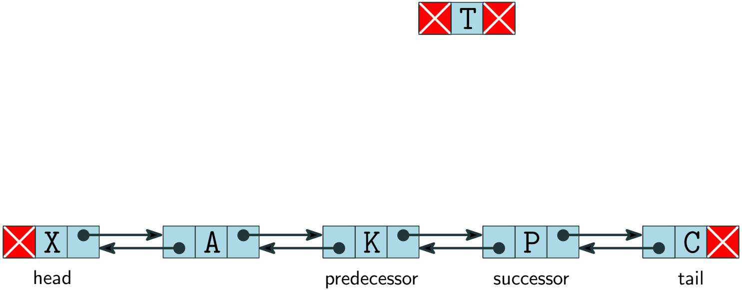
```
public class DoublyLinkedList<E> implements
                Iterable<E>
```

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() {...}`

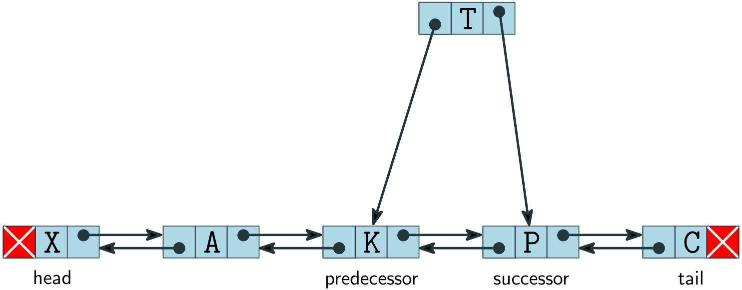
Illustrating `addBetween(E e, Node<E> predecessor, Node<E> successor)`



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



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



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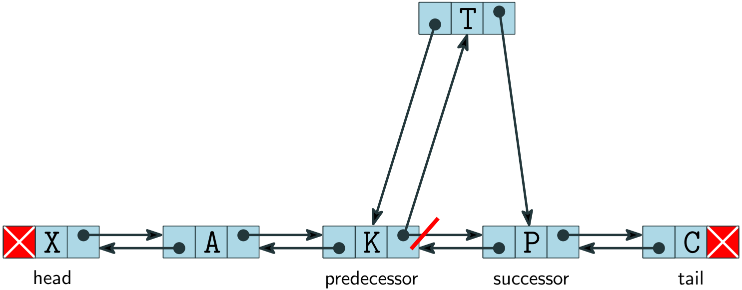

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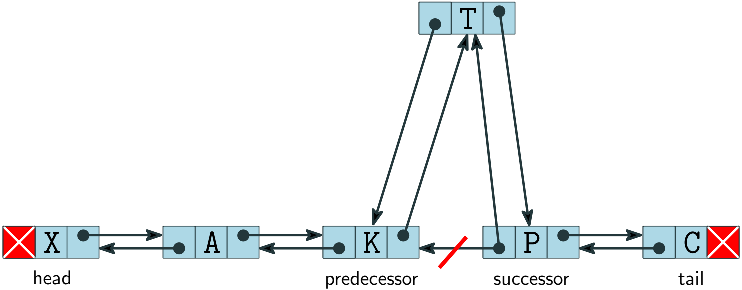

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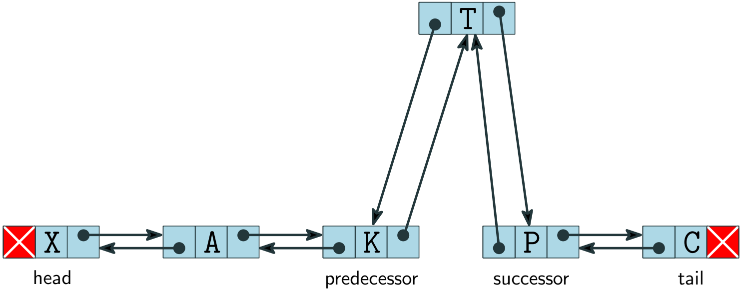

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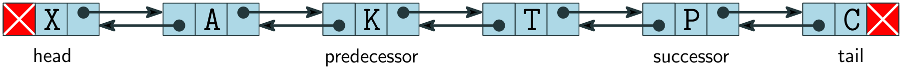


DoublyLinkedList<E>

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;
}
```

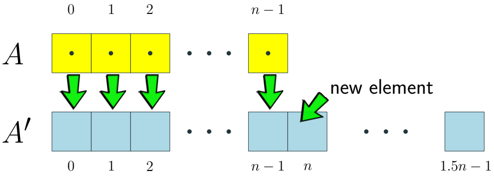
- Linked lists can take substantially more space per data element compared to arrays and `ArrayLists` since every node is storing at least one link (reference to another node in the same list)
- Linked lists are slower than `ArrayLists`, especially when trying to execute many insertions at a go; every 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.

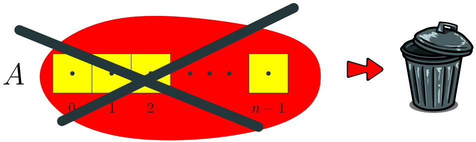
SLLs vs ArrayLists

```java
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	1
100	7
$1,000$	13
$10,000$	19
$100,000$	24
$1,000,000$	30
$10,000,000$	36

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

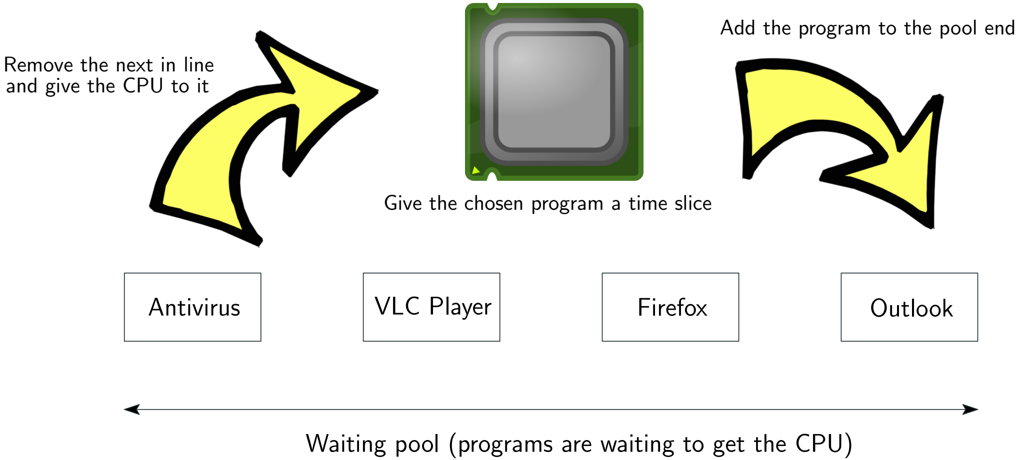
Why is the `StringBuilder` class so much faster than `String` class?

- **`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!

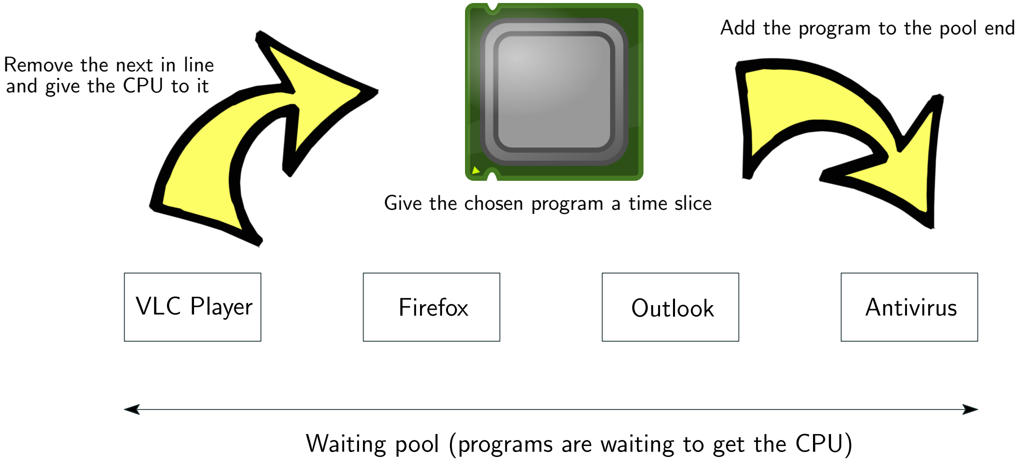
Maintaining a cyclic order

- 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



Remove the next in line
and give the CPU to it
Give the chosen program a time slice
Add the program to the pool end
Antivirus
VLC Player
Firefox
Outlook
Waiting pool (programs are waiting to get the CPU)


Remove the next in line
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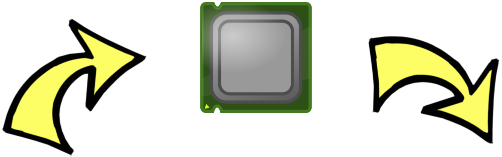
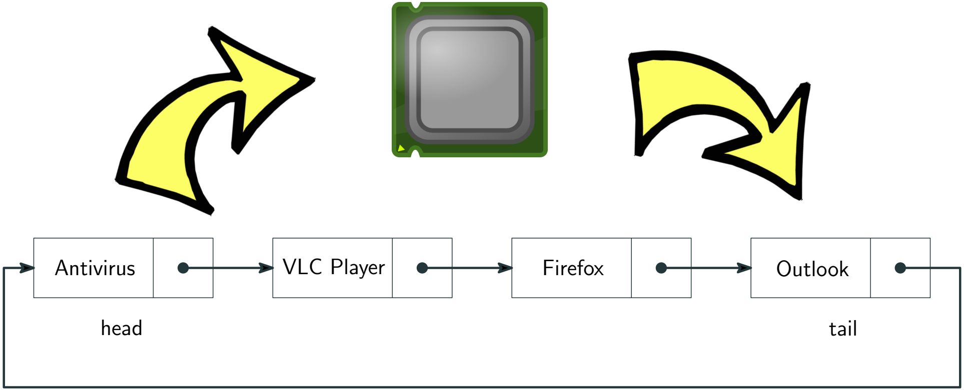
Waiting pool (programs are waiting to get the CPU)

Idea! make the tail point to the head

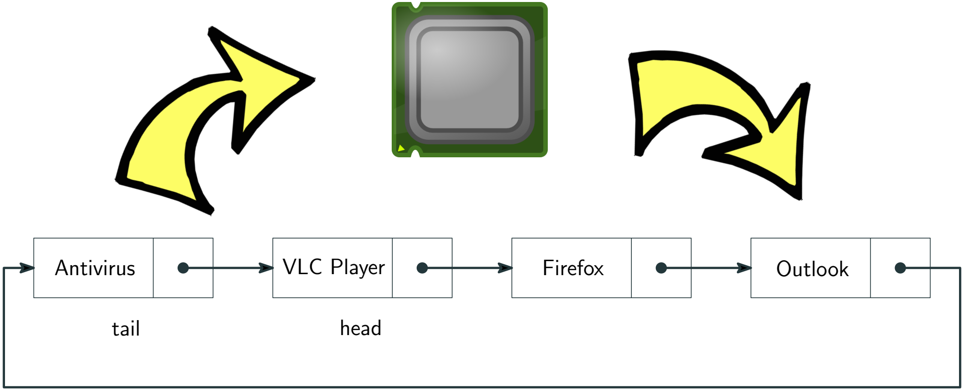


Antivirus	•	→	VLC Player	•	→	Firefox	•	→	Outlook	•
head									tail	

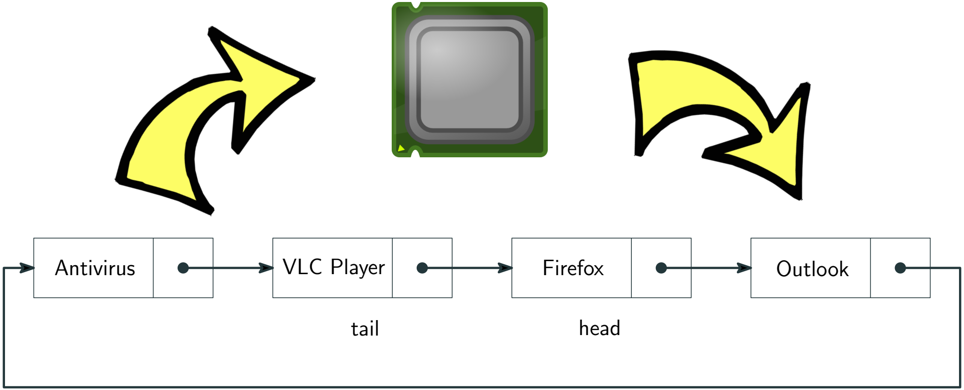
Circular linked list



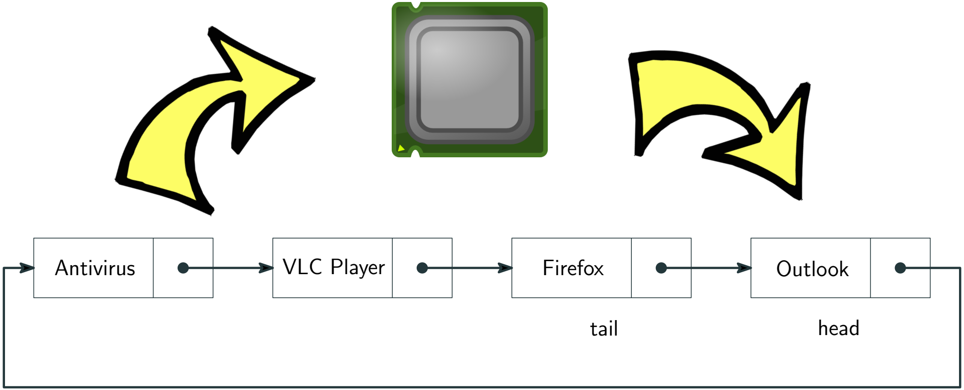
Circular linked list



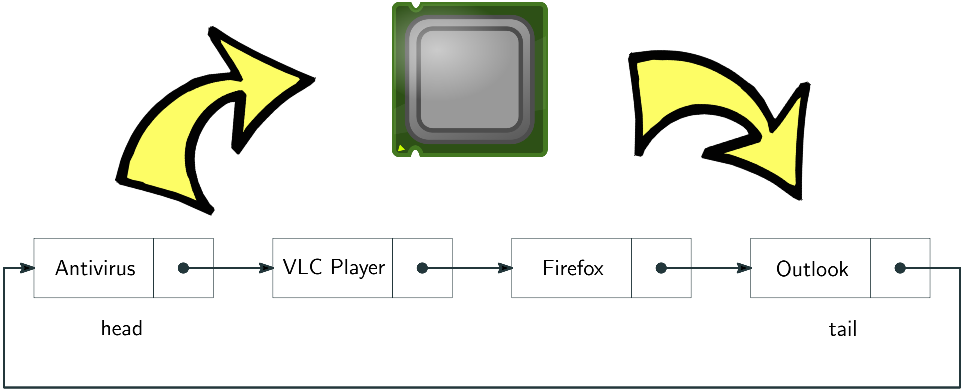
Circular linked list



Circular linked list



Circular linked list



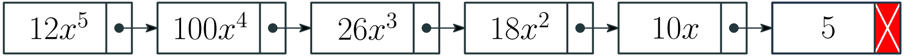
Methods

public class CircularLinkedList<E> implements Iterable<E>

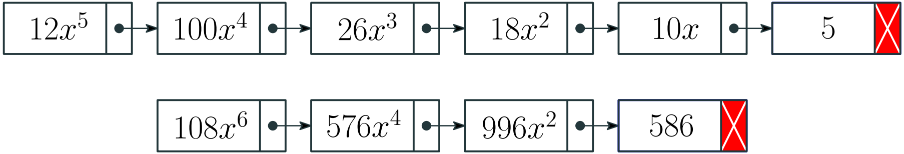
1. `int size() {...}`, **Time complexity**: $O(1)$
2. `boolean isEmpty() {...}`, **Time complexity**: $O(1)$
3. `E first() {...}`, **Time complexity**: $O(1)$
4. `E last() {...}`, **Time complexity**: $O(1)$
5. `void rotate() {...}`, **Time complexity**: $O(1)$
6. `void addFirst(E e) {...}`, **Time complexity**: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

Representing polynomials using linked lists

- Polynomials can be effectively represented using linked lists where every node holds a polynomial term. The terms are **reversely sorted** based on their exponents. For example, the polynomial $p(x) = 12x^5 + 100x^4 + 26x^3 + 18x^2 + 10x + 5$ is represented as:



- Now, we will see how to add two polynomials represented using two different linked-lists. Example:



- Let the two input polynomials be denoted by $p(x)$ and $q(x)$. The objective is to compute a linked-list representation of $r(x) = p(x) + q(x)$, when the two linked-list representations of $p(x)$ and $q(x)$ are supplied.
- If $q(x) = 0$, return $p(x)$ since in this case, $r(x) = p(x) + q(x) = p(x) + 0 = p(x)$. Similarly, if $p(x) = 0$, return $q(x)$.

Algorithm

Computing $r(x) = p(x) + q(x)$

```
nextTermFromP = p.head.term, nextTermFromQ = q.head.term;
while( there are un-scanned nodes both in p and q) {
    if( nextTermFromP.exponent == nextTermFromQ.exponent  ) {
      Add nextTermFromP and nextTermFromQ and append a new node with the result term
      in the linked-list r. Update nextTermFromP and nextTermFromQ using the next two
      terms from the polynomials p and q, respectively;
    }
    else if( nextTermFromP.exponent > nextTermFromQ.exponent ) {
         Append a new node with the term nextTermFromP in the linked-list r
         and update nextTermFromP using the next term from p;
    }
    else {
         Append a new node with the term nextTermFromQ in the linked-list r
         and update nextTermFromQ using the next term from q;
    }
}
If there are un-scanned nodes from p, send those to r (using a loop);
If there are un-scanned nodes from q, send those to r (using a loop);
```

Efficiency

- Assume that there are m nodes in $p(x)$'s linked-list and n in $q(x)$'s linked-list
- Total work done by the algorithm is proportional to the number of nodes in both the linked-lists. To see this observe that we visit every node in both the lists exactly once.
- The `addLast()` method is invoked no more than $n+m$ times and each such call takes $O(1)$ time.
- Every iteration of the while-loop takes $O(1)$ time. So, the total time taken by the while-loop is $O(m+n)$ since it iterates at most $n+m$ times.
- Line 17: runs in $O(m)$ time and line 18: in $O(n)$ time.
- Therefore, the runtime of the add algorithm is:

$$O(m+n)+O(m)+O(n)=O(2m+2n)=O(2(m+n))=O(m+n)$$

See the class `Polynomial` to see how polynomial addition algorithm can be implemented efficiently

The `Cloneable` interface

- Cloning an array is not difficult since we can simply use the `clone()` method on it (does deep-copy for **primitives** and shallow-copy for **non-primitives**)
- What if we want to clone an object of an user-defined class X? We need to make the class X cloneable so the `clone()` method can be invoke on it.

```java
// Reference: https://docs.oracle.com/en/java/javase/17/docs//api/java.base/java/lang/Cloneable.html
public class Polynomial implements Cloneable, Iterable<Polynomial.PolynomialTerm> {
   // other variables and methods

    public Polynomial clone() throws CloneNotSupportedException {
       var clonePolynomial = (Polynomial) super.clone();

       clonePolynomial.L = new SinglyLinkedList<>();
       for( var term : L ) // create identical terms in the clone
          clonePolynomial.L.addLast( new PolynomialTerm(term.coefficient, term.exponent) );
       return clonePolynomial;
    }
}
```

- Inside the `clone()` method, ensure you set up every instance variable of the clone object appropriately; otherwise, the cloned object will not be a replica!

Recommended

Make the `SinglyLinkedList` and `DoublyLinkedList` classes cloneable

Chapter 5 from

`https://opendsa-server.cs.vt.edu/OpenDSA/Books/CS3/html/`