# CompSci 201, L10: Memory, Pointers, LinkedList

# Summer course book bagging is open – course offerings in CS

Summer Term 1 (May 17 – June 29)

- **CS/ECE 250D Computer Architecture**
  - Computer structure, assembly language, instruction execution, addressing techniques, and digital representation of data. Computer system organization, logic design, microprogramming, cache and memory systems, and input/output interfaces. Prerequisite: Computer Science 201.

Summer Term 2 (July 3 – August 13)

- **CS 230 Discrete Math**
  - Mathematical notations, logic, and proof; linear and matrix algebra; graphs, digraphs, trees, representations, and algorithms; counting, permutations, combinations, discrete probability, Markov models; advanced topics from algebraic structures, geometric structures, combinatorial optimization, number theory. Pre/corequisite: Computer Science 201.

# Announcements, Coming up

- Today, Wednesday 2/15
  - APT 4 due
- Next Monday 2/20
  - Project P2: Markov due
- Next Wednesday 2/22
  - APT **Quiz 1** due

# What is an APT Quiz?

- Set of 3 APT problems, 2 hours to complete.
  - Will be available starting this Saturday afternoon (look for a Sakai/email announcement)
  - Must *complete* by 11:59 pm Wednesday 10/19 (so start before 10)

- Start the quiz on Sakai assessments tool, begins your timer and shows you the link to the problems and submission page.
  - Will look/work just like the regular APT page, just with only 3 problems.

# What is allowed?

**Yes, allowed**

- Zybook
- Course notes
- API documentation
- VS Code
- JShell

**No, not allowed**

- Collaboration or sharing any code.
- Communication about the problems ***at all*** during the window.
- Searching internet, stackoverflow, etc. for solutions.

# Don’t do these things

1. Do not collaborate. Note that we log all code submissions and will investigate for academic integrity.

2. Do not hard code the test cases (if(input == X) return Y, etc.).

   We show you the test cases to help you debug. But we search for submissions that do this and **you will get a 0 on the APT quiz if you hard code the test cases** instead of solving the problem.

# How is it graded?

Not curved, adjusted. 3 problems, 10 points each.

| Raw score R out of 30. | Adjusted score A out of 30. | 100 point grade scale |
|---|---|---|
| 27 <= R <= 30 | A = R | 90 – 100 |
| 24 <= R <= 26 | A = 26 | ~87 |
| 21 <= R <= 23 | A = 25 | ~83 |
| 18 <= R <= 20 | A = 24 | 80 |
| 15 <= R <= 17 | A = 23 | ~77 |
| 12 <= R <= 14 | A = 22 | ~73 |
| 9 <= R <= 11 | A = 21 | 70 |
| 6 <= R <= 8 | A = 20 | ~67 |
| 3 <= R <= 5 | A = 19 | ~63 |
| 1 <= R <= 2 | A = 18 | 60 |

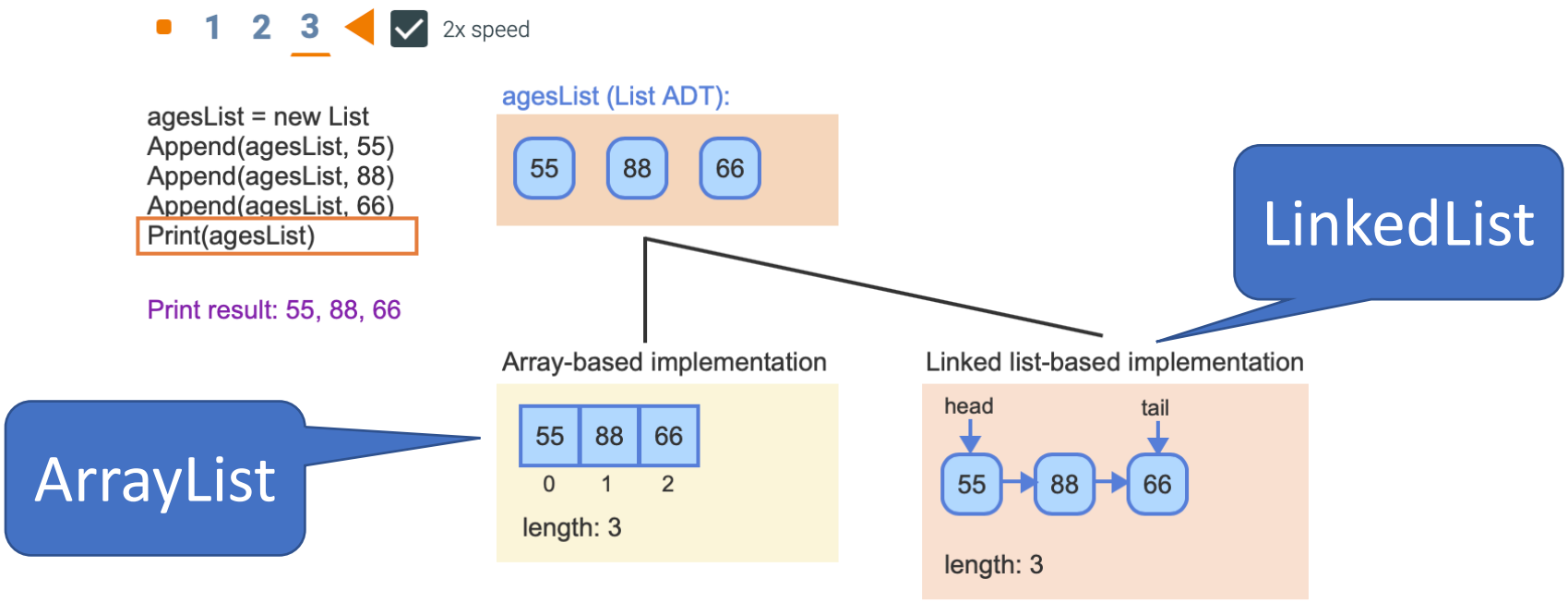
Can still get in the B range even if you can't solve one; don't panic!

Only going to get a 0 if you collaborate or hard code test cases. Don't do it!

# Linked List, API Perspective

# Multiple Implementations of the Same Interface

2.4.1: List ADT using array and linked lists data structures.




A list ADT is commonly implemented using array and linked list data structures. But, a programmer need not have knowledge of which data structure is used to use the list ADT.

# Motivating List Interface Implementations by Efficiency

- `List<String> a = new LinkedList<>();`
- `List<String> b = new ArrayList<>();`

You already know how to use a List, same exact methods and functionality with LinkedList!

- Implementation? ArrayList implements List using Array, LinkedList implements List using…"links"?
- Tradeoffs? Which is more efficient (for ___)?

# ArrayList uses Array. Fast random access memory, fast get()

- Accessing Array (or ArrayList `get(i)`) at index i takes the same time whether:
  - i=1, 201, 2001, …
- Possible because Java compiler knows:
  - Where in memory the array starts (say position X),
  - array is laid out consecutively, all together, in memory,
  - Memory each value takes (say 4 bytes per int).
- Allows to calculate the memory position of `myArray[i]` in constant time (more in CS 210/250).

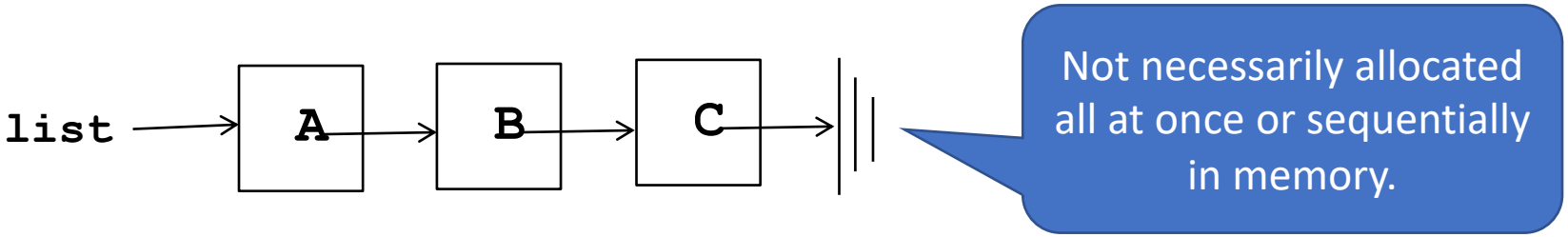
# Pros/Cons of Array-Based Data Structures

| Array-Based Data Structure | What array? |
|---|---|
| `ArrayList` | Array of list elements |
| `String/StringBuilder` | Array of characters |
| `HashSet/Map` | Array of buckets |

| Pros | Cons |
|---|---|
| O(1) lookup by index | Hard to add/remove except at the end. |
| Little memory overhead, just storing elements | Adding elements gives amortized (averaged) efficiency, not worst case. |

# What is a (singly) linked list conceptually?

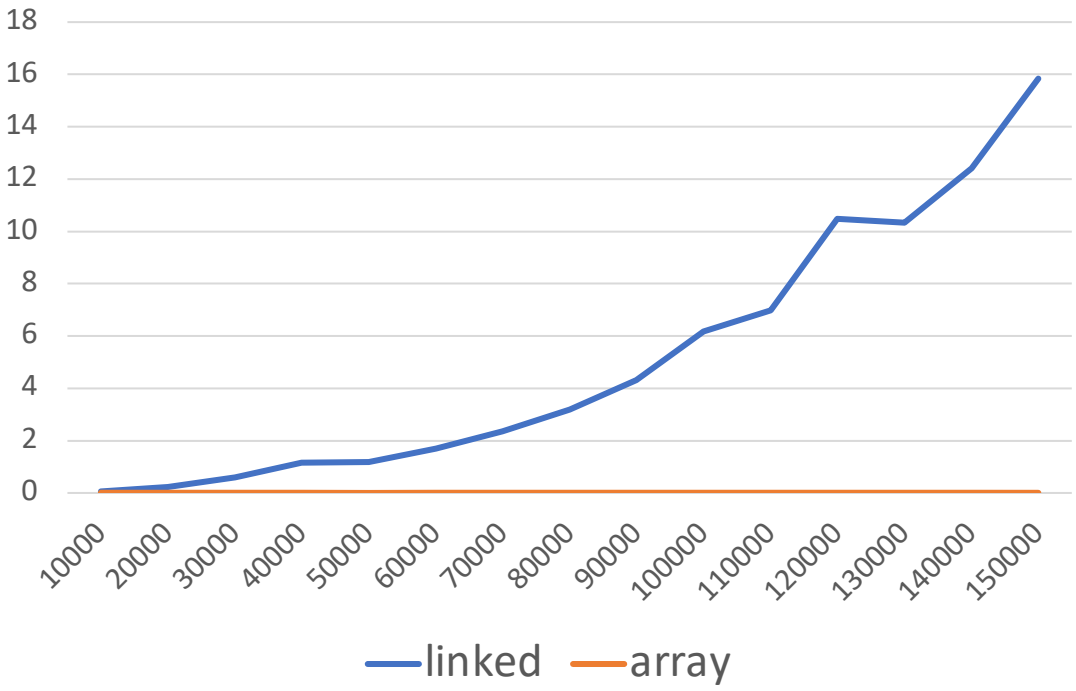
A reference (~pointer) to the *first* node in a list, connected by a reference (~pointer) to the next node.




No constant time access to nodes in the middle. To get C, start at A, follow the references (~pointers).

# ArrayList much faster than LinkedList for Random Access `.get()` operations

| list size | linked | array |
|---|---|---|
| 10000 | 0.0583 | 0.0012 |
| 20000 | 0.223 | 0.0014 |
| 30000 | 0.6 | 0.0009 |
| 40000 | 1.1643 | 0.0008 |
| 50000 | 1.1847 | 0.0007 |
| 60000 | 1.703 | 0.001 |
| 70000 | 2.3685 | 0.0013 |
| 80000 | 3.1883 | 0.0015 |
| 90000 | 4.3096 | 0.0017 |
| 100000 | 6.1647 | 0.0021 |
| 110000 | 6.9777 | 0.0038 |
| 120000 | 10.4757 | 0.0026 |
| 130000 | 10.3337 | 0.003 |
| 140000 | 12.4032 | 0.0032 |
| 150000 | 15.8398 | 0.0059 |

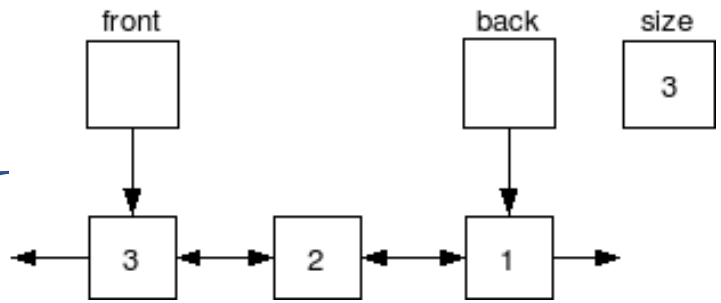


# LinkedList `.get()` runtime explained

- Calling **`list.get(k)`** is O(N) for LinkedList
  - Not quite, O(min(*k, size-k),* doubly-linked list
  - **`list.get(k)`** is O(1) for ArrayList
- To get every element one at a time:
  - Linked: $2(1 + 2 + \ldots + N/2)$ is $O(N^2)$
  - Array: $1 + 1 + \ldots + 1$ is O(N)

"average" case is still O(N)

Java API LinkedList is actually doubly-linked, pointers forward and back.



# `get()` vs. Iterator

For LinkedList `lList` of N integers…

```
17    // Looping with get
18    for (int i=0; i<N; i++) {
19        total += lList.get(i);
20    }
21
22    // Looping with iterator (implicit)
23    for (int val : lList) {
24        total += val;
25    }
26
27    // Looping with iterator (explicit)
28    Iterator<Integer> listIter = lList.iterator();
29    while (listIter.hasNext()) {
30        total += listIter.next();
31    }
```

This loop is $O(N^2)$

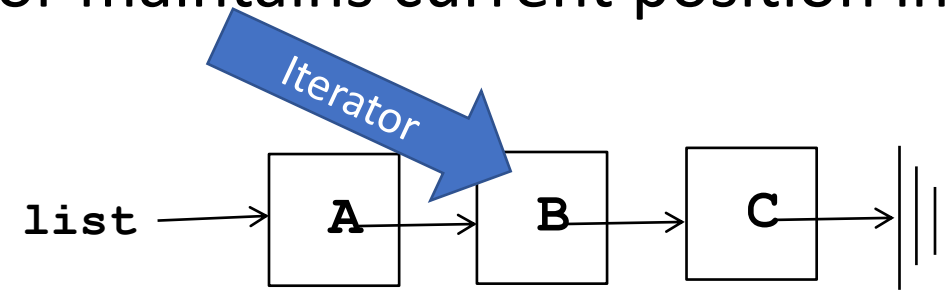
| N | Runtime in s Using get | Runtime in s with Iterator |
|---|---|---|
| 25k | 0.2 | 0.0 (rounding) |
| 50k | 0.9 | 0.0 (rounding) |
| 100k | 3.9 | 0.0 (rounding) |
| 200k | 16.2 | 0.0 (rounding) |

These loops are O(N)

Equivalent to second loop, hasNext and next just like Scanner

# What is an Iterator conceptually?

- get()  method always starts at the front of the list.
- Iterator maintains current position in list.




**Looping with get()**

get(i) → Start at beginning, iterate over i-1 elements.

**Looping with iterator**

Next element where iterator is pointing, then advance iterator.

# Are LinkedLists just worse? Removing from the front

For LinkedList `lList` and ArrayList `aList` of N integers…

```
double before = System.nanoTime();
for (int t=0; t<n; t++) {
    lList.remove( index: 0);
}
double after = System.nanoTime();
System.out.println((after-before)/1e9);
```

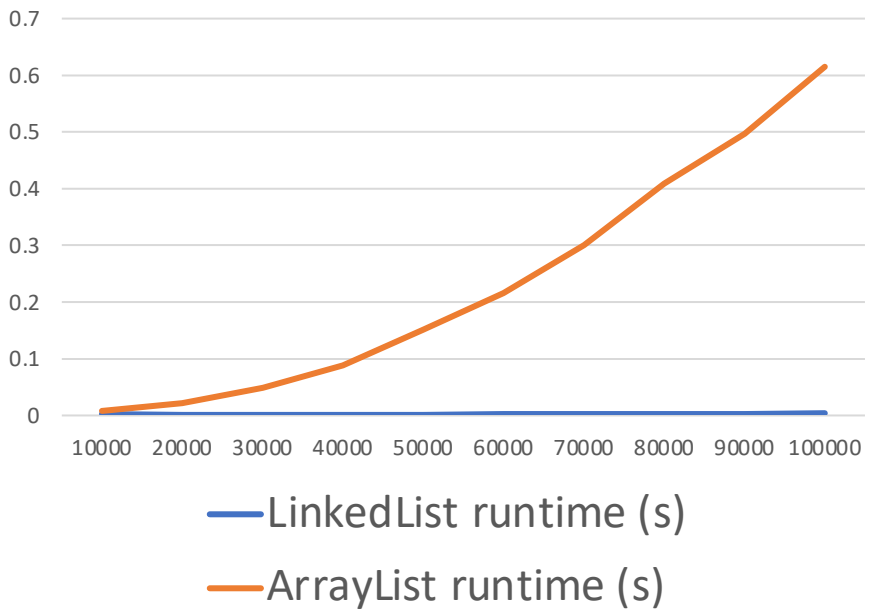
VS

```
before = System.nanoTime();
for (int t=0; t<n; t++) {
    aList.remove( index: 0);
}
after = System.nanoTime();
System.out.println((after-before)/1e9);
```

Timing repeatedly removing from the front…

# LinkedList remove/add to front empirical results

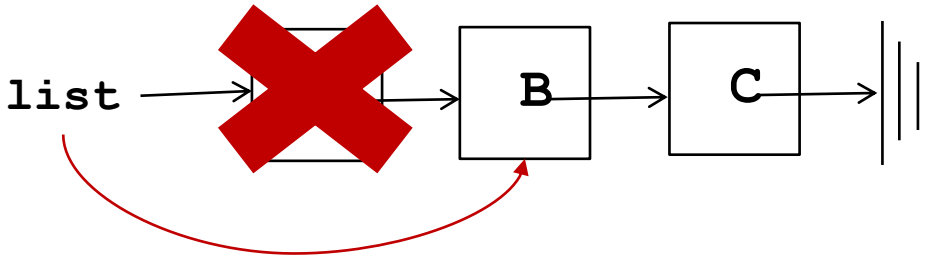
| List Size | LinkedList runtime (s) | ArrayList runtime (s) |
|---|---|---|
| 10000 | 0.002 | 0.008 |
| 20000 | 0.001 | 0.022 |
| 30000 | 0.001 | 0.049 |
| 40000 | 0.001 | 0.088 |
| 50000 | 0.001 | 0.152 |
| 60000 | 0.002 | 0.216 |
| 70000 | 0.003 | 0.301 |
| 80000 | 0.003 | 0.409 |
| 90000 | 0.003 | 0.497 |
| 100000 | 0.004 | 0.615 |



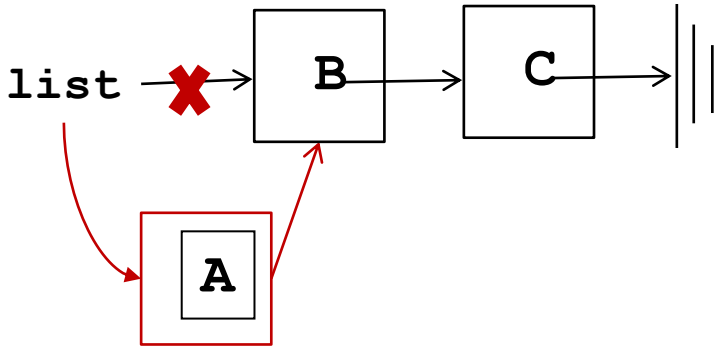

LinkedList add/remove to front are O(1) (so remove N from front is O(N)

# Explaining fast remove/add to front for LinkedList

To remove from the front, Just update list to point to the second element. No other shifting!




To add to the front, just make a new node pointing to the second element. No shifting!



# WOTO

## Go to duke.is/6xepp

Not graded for correctness, just participation.

Try to answer *without* looking back at slides and notes.

But do talk to your neighbors!

2

What is the runtime complexity of the reverseCopy method as a function of n where n is the size of myList? *

```
22    public static List<Integer> reverseCopy(LinkedList<Integer> myList) {
23        List<Integer> reversed = new LinkedList<>();
24        for (Integer val : myList) {
25            // adds val to front of list
26            reversed.add(0, val);
27        }
28        return reversed;
29    }
```

- ◯ O(1)
- ✓ O(n)
- ◯ O(n^2)
- ◯ O(n^3)

3

What is the runtime complexity of the removeZeros method be as a function of n, the number of elements in the list? Answer in the worst case / without making any assumptions about the elements of the input myList. *

```
8    public static void removeZeros(LinkedList<Integer> myList) {
9        for (int i=0; i<myList.size(); i++) {
10           if (myList.get(i) == 0) {
11               myList.remove(i);
12           }
13       }
```

- ◯ O(1)
- ◯ O(n)
- ✓ ◯ O(n^2)
- ◯ O(n^3)

4

What is the runtime complexity of the removeZeros method be as a function of n, the number of elements in the list? Answer in the worst case / without making any assumptions about the elements of the input myList.

The Java API documentation clarifies that the remove() method on an Iterator "Removes from the underlying collection the last element returned by this iterator." *

```
6   public static void removeZeros(LinkedList<Integer> myList) {
7       Iterator<Integer> listIter = myList.iterator();
8       while (listIter.hasNext()) {
9           if (listIter.next() == 0) {
10              listIter.remove();
11          }
12      }
13  }
```

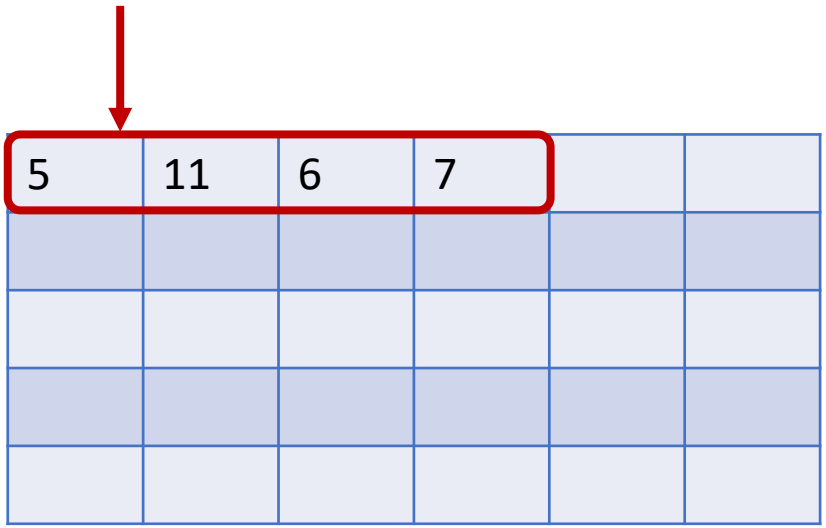
- ◯ O(1)
- ✓ O(n)
- ◯ O(n^2)
- ◯ O(n^3)

# Linked List, Low-level DIY perspective

# Contrasting how things look to your computer / in memory

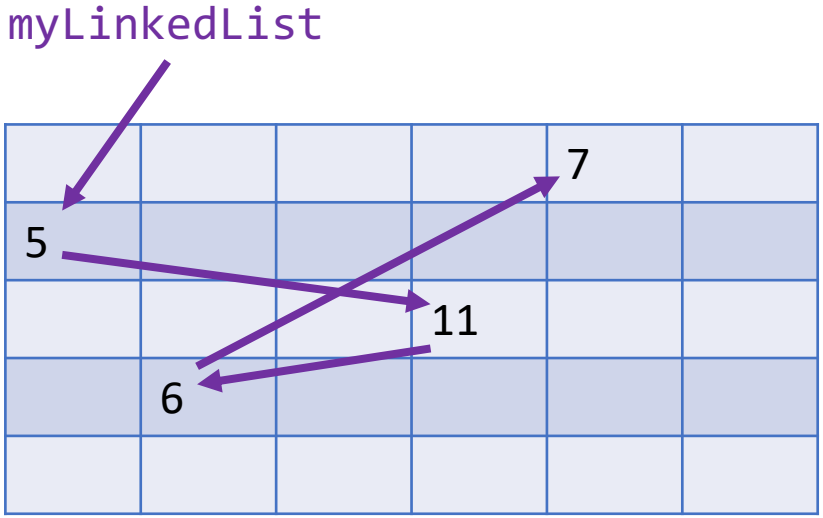
**Array/ArrayList**

Elements laid out sequentially, one at a time, in order, in memory.




**LinkedList**

Elements at *arbitrary* locations in memory, connected only by references to the next element.

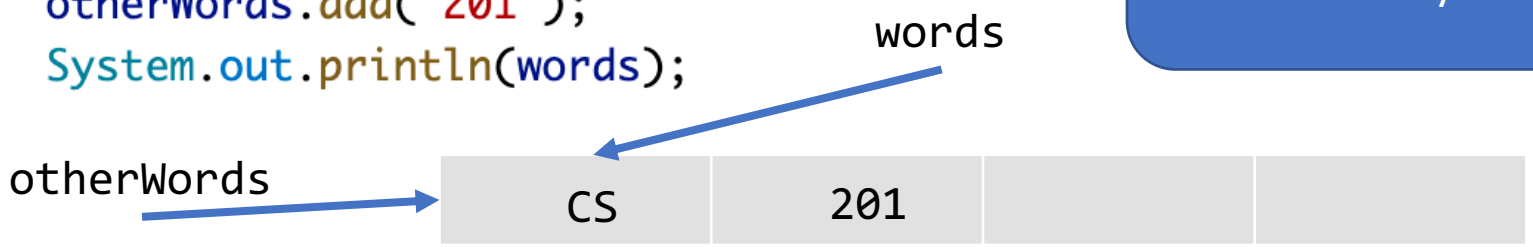


# Memory and references

- In Java, **variables for *reference types*** (anything that is an object/not a primitive) really **store the location of the object in memory**.
- Can have *multiple references* to the same object in memory!

```
 6      List<String> words = new LinkedList<>();
 7      words.add("CS");
 8      List<String> otherWords = words;
 9      otherWords.add("201");
10      System.out.println(words);
```

Prints [“CS”, “201”], only one actual List in memory!



# Multiple objects or multiple references

Java creates a reference type object in memory only when the code calls the new operator.

```
11      List<String> listA = new LinkedList<>();
12      List<String> listB = new LinkedList<>();
```

First example create 2 *distinct* empty lists, but…

```
11      List<String> listA = new LinkedList<>();
12      List<String> listB = listA;
```

Second example creates *one* list in memory with two references / variable names.

# Pass by value of reference

```
12    public static void removeFront(List<String> words) {
13        words.remove(0);
14    }
```

- Java does NOT copy all of `words` when we call this method.
- Copies the *reference* (memory address) and passes that, O(1) time [memory addresses are 64 bits].
- Changes relevant outside of method.

```
6     List<String> words = new LinkedList<>();
7     words.add("CS");
8     removeFront(words);
9     System.out.println(words);
```

Prints [] (empty), change to words in method changes the only List in memory. Different for primitive types.

# More Pass by value of reference

- Why does it matter that Java passes a *copy* of the reference to methods?
- Cannot "lose" a reference inside a method.

```
16    public static void tryBreakReference(List<String> words) {
17        words = new LinkedList<>();
18    }
```

Even though this reassigns words in the method…

```
6     List<String> words = new LinkedList<>();
7     words.add("CS");
8     tryBreakReference(words);
9     System.out.println(words);
```

Still prints ["CS"], only the *copy* of the reference was reassigned.

# Null reference/pointer

- The default value for an uninitialized (no memory allocated by a call to new) object is **`null.`**

- Can check if an object `== null`.
  - We will use to denote the end of a linked list, the node with no more nodes following.

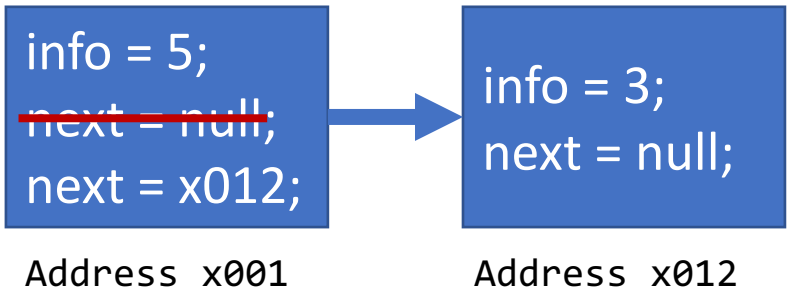
- If you try to call any methods on a null object, will get a **null pointer exception error**.

# Linked list is a list implemented by linked nodes. What is a node?

- Just a Java object of a class we write, like any other!
- We want to "link" them together, so each node has a *pointer* (really a reference = a memory location) to another node.

```
public class ListNode {
    int info;
    ListNode next;
    ListNode(int x){
        info = x;
    }
    ListNode(int x, ListNode node){
        info = x;
        next = node;
    }
}
```

```
ListNode first = new ListNode(5);
ListNode second = new ListNode(3);
first.next = second;
```



# Creating Nodes, constructing lists

1. Calling `new Node(…)` always creates a Node in memory that did not exist before

2. Writing `node.next = otherNode;` makes node → (point to) otherNode

3. `node.next` or `node.info` gives an error (null pointer exception) if node is null

# WOTO

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Not graded for correctness, just participation.

Try to answer *without* looking back at slides and notes.

But do talk to your neighbors!

2

This and following questions reference the ListNode class shown. Suppose we run the following code:

ListNode myList =new ListNode(2, new ListNode(0, new ListNode(1)));

What is myList.next.next? *

```java
public class ListNode {
    int info;
    ListNode next;
    public ListNode(int info) {
        this.info = info;
    }
    public ListNode(int info, ListNode next) {
        this.info = info;
        this.next = next;
    }
}
```

- ◯ 0
- ◯ The second ListNode object
- ◯ 1
- ✓ The third ListNode object
- ◯ null

3

Again suppose we run the following code.

ListNode myList =new ListNode(2, new ListNode(0, new ListNode(1)));

What is myList.next.info? *

- [x] 0
- [ ] The second ListNode object
- [ ] 1
- [ ] The third ListNode object
- [ ] null

4

Again suppose we run the following code.

ListNode myList =new ListNode(2, new ListNode(0, new ListNode(1)));

What is myList.next.next.next? *

- [ ] 1
- [ ] The third ListNode object
- [x] null
- [ ] error, null pointer exception

5

Consider the following code. assume the printList method prints the values in a list (meaning everything from a given starting ListNode and following next references until reaching null). What would be printed by **line 18**, which prints **ret**? *

```
 9      public static ListNode foo(ListNode list) {
10          list = list.next;
11          list.next = null;
12          return list;
13      }
14
        Run | Debug
15      public static void main(String[] args) {
16          ListNode list = new ListNode(info: 2, new ListNode(info: 0, new ListNode(info: 1)));
17          ListNode ret = foo(list);
18          printList(ret);
19          printList(list);
20      }
```

- ◯ nothing
- ◯ 0
- ◯ 2, 0
- ◯ 2, 0, 1

6

Same code. What would be printed by **line 19**, which prints **list**? *

```
 9      public static ListNode foo(ListNode list) {
10          list = list.next;
11          list.next = null;
12          return list;
13      }
14
        Run | Debug
15      public static void main(String[] args) {
16          ListNode list = new ListNode(info: 2, new ListNode(info: 0, new ListNode(info: 1)));
17          ListNode ret = foo(list);
18          printList(ret);
19          printList(list);
20      }
```

- ◯ nothing
- ◯ 0
- ◯ 2, 0
- ◯ 2, 0, 1