CSE 220
Data Structures

Lecture 02:
Linked List Primer

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Review: Time and Space Complexity

- Big-O is like a "*speedometer*" for your code.
  - It tells you **how fast your code runs** or **how much memory it uses** as the input grows.
  - **It's Not Exact:** Big-O doesn't count every single step. Instead, it gives you a general idea of how your code scales.
- Example:
  - If your code takes $3n^2 + 2n + 1$ steps, Big-O simplifies it to $O(n^2)$
  - Why? Because as n gets really big, the n^2 part dominates the others

Exercise

```java
public void test1(int[] arr) {  no usages
    for (int i = 0; i < arr.length; i++) {
        System.out.println(arr[i]);
    }
}
```

Exercise

TC: O(n)
SC: O(1)

```java
public void test1(int[] arr) {  no usages
    for (int i = 0; i < arr.length; i++) {
        System.out.println(arr[i]);
    }
}
```

Exercise

```java
public void test1_a(int[] arr) {  no usages
    // Make a copy of the array
    int[] copy = Arrays.copyOf(arr, arr.length);
    // print first 10 elemements
    for (int i = 0; i < 10; i++) {
        System.out.println(copy[i]);
    }

}
```

Exercise

TC: O(n)
SC: O(n)

```
public void test1_a(int[] arr) {  no usages
    // Make a copy of the array
    int[] copy = Arrays.copyOf(arr, arr.length);
    // print first 10 elemements
    for (int i = 0; i < 10; i++) {
        System.out.println(copy[i]);
    }

}
```

Exercise

```java
public void test1_b(int rows, int cols) {
    int size = rows * cols;
    int[][] matrix = new int[rows][cols];
    for (int i = 0; i < size; i++) {
        int row = i / cols;
        int col = i % cols;
        matrix[row][col] = i;
    }
}
```

Exercise

TC: $O(n^2)$

SC: $O(n^2)$

```
public void test1_b(int rows, int cols) {
    int size = rows * cols;
    int[][] matrix = new int[rows][cols];
    for (int i = 0; i < size; i++) {
        int row = i / cols;
        int col = i % cols;
        matrix[row][col] = i;
    }
}
```

Exercise

```java
public void test2(int n) {  no usages
    for (int i = 0; i < n; i++) {
        for (int j = 0; j < 100; j++) {
            for (int k = 0; k < n; k++) {
                System.out.println("Some operation...");
            }
        }
    }
}
```

Exercise

TC: $O(n^2)$
SC: O(1)

```java
public void test2(int n) {  no usages
    for (int i = 0; i < n; i++) {
        for (int j = 0; j < 100; j++) {
            for (int k = 0; k < n; k++) {
                System.out.println("Some operation...");
            }
        }
    }
}
```

Exercise

```java
public void test3(int[] sortedArr, int[] valuesToFind) {  no usages
    for (int i : valuesToFind) {
        // binary search
        int idx = Arrays.binarySearch(sortedArr, i);
        if (idx >= 0) {
            System.out.println("Value found at index: " + idx);
        } else {
            System.out.println("Value not found");
        }
    }
}
```

Exercise

TC: O(nlogn)
SC: O(1)

```java
public void test3(int[] sortedArr, int[] valuesToFind) {  no usages
    for (int i : valuesToFind) {
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        int idx = Arrays.binarySearch(sortedArr, i);
        if (idx >= 0) {
            System.out.println("Value found at index: " + idx);
        } else {
            System.out.println("Value not found");
        }
    }
}
```

Exercise

```
public ArrayList<ArrayList<Integer>> findPowerSets(int[] arr) {   1 usage
    int n = arr.length;
    int total = 1 << n;
    ArrayList<ArrayList<Integer>> powerSet = new ArrayList<>();
    for (int i = 0; i < total; i++) {
        ArrayList<Integer> subset = new ArrayList<>();
        for (int j = 0; j < n; j++) {
            if ((i & (1 << j)) > 0) {
                subset.add(arr[j]);
            }
        }
        powerSet.add(subset);
    }
    return powerSet;
}
```

Exercise

TC: $O(n \cdot 2^n)$
SC: $O(n \cdot 2^n)$

```
public ArrayList<ArrayList<Integer>> findPowerSets(int[] arr) {  1 usage
    int n = arr.length;
    int total = 1 << n;
    ArrayList<ArrayList<Integer>> powerSet = new ArrayList<>();
    for (int i = 0; i < total; i++) {
        ArrayList<Integer> subset = new ArrayList<>();
        for (int j = 0; j < n; j++) {
            if ((i & (1 << j)) > 0) {
                subset.add(arr[j]);
            }
        }
        powerSet.add(subset);
    }
    return powerSet;
}
```

Goal

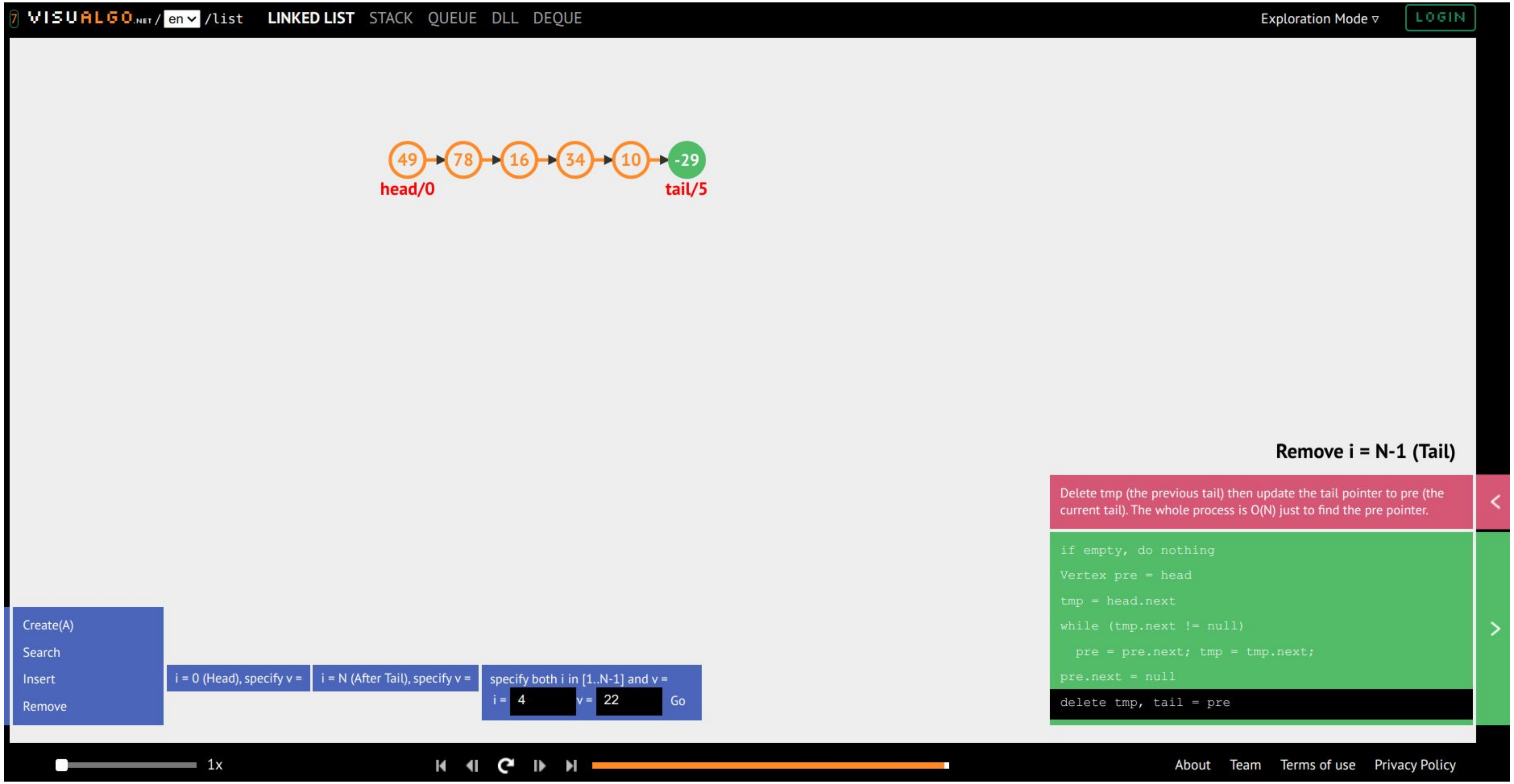
- Design data structures that lets us perform the following tasks in an efficient way:
  - **Insertion** of a new element
  - **Deletion** of an existing element
  - **Checking** if an element exists
  - **Modification** of an existing element
  - Finding the **minimum** / **maximum** element
- There is no “one size fits all” solution!

Arrays vs. Linked Lists

- Arrays:
  - Fixed size (static).
    - Insertion/deletion is expensive (requires shifting elements).
    - Random access is fast ⇒ $O(1)$.
- Linked Lists:
  - Dynamic size (grows/shrinks as needed).
    - Insertion/deletion is efficient ($O(1)$ at head/tail).
    - Sequential access (no random access, $O(n)$ for traversal).

Interactive Visualization

https://visualgo.net/en/list

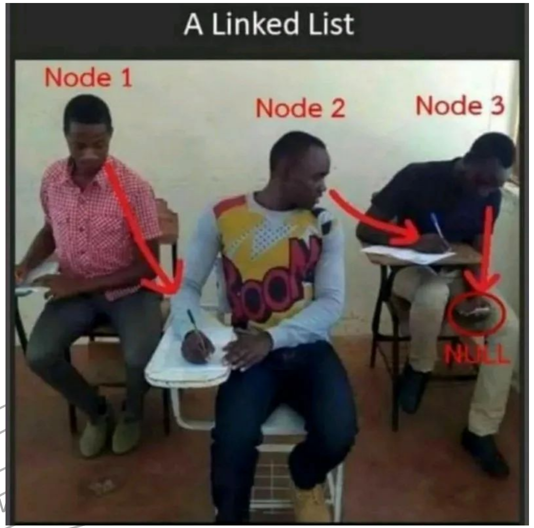


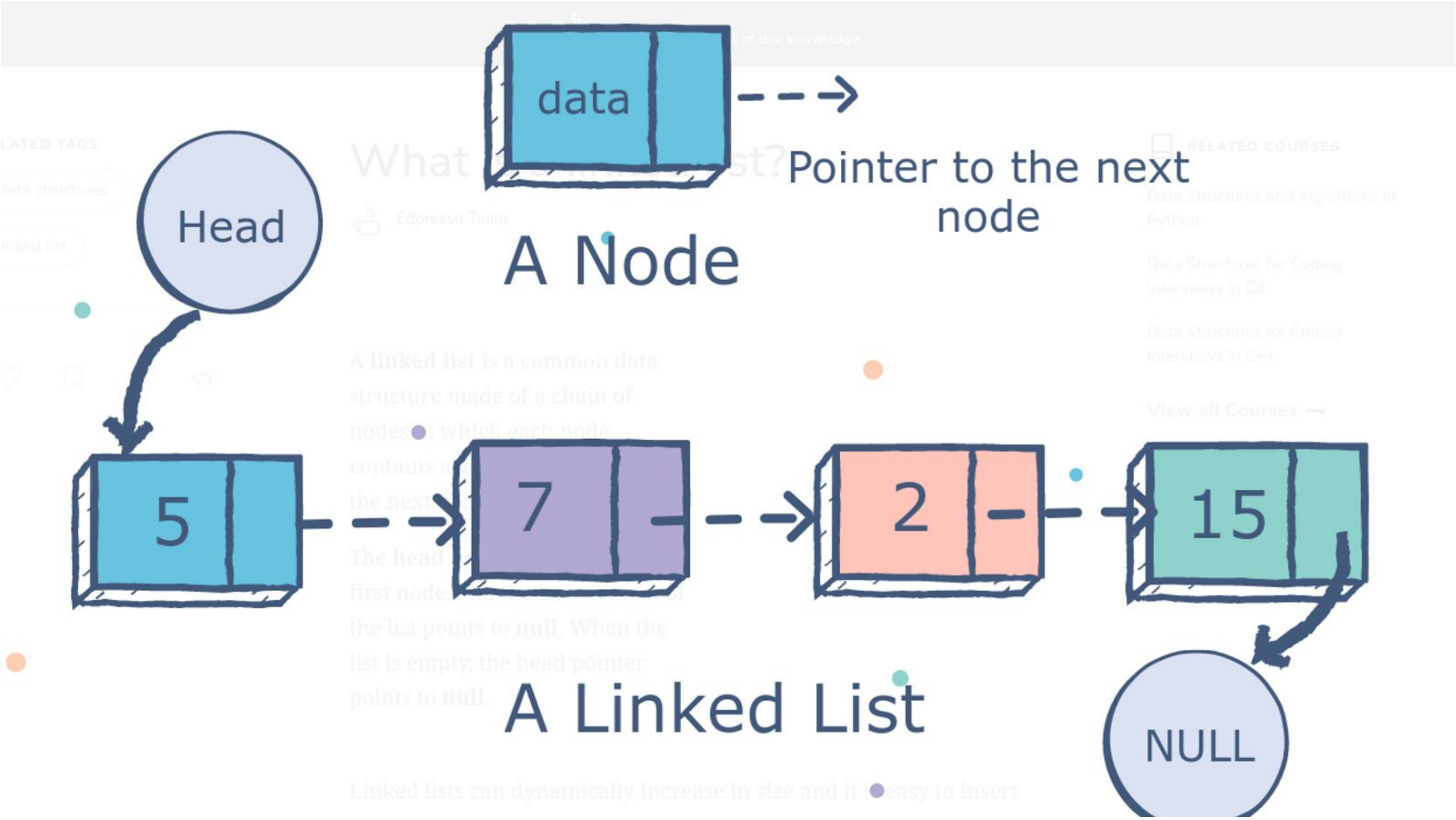
Linked List Overview

A node is the building block for linked lists.

Contains two key things:

1. **Data**
2. **Reference to next node**



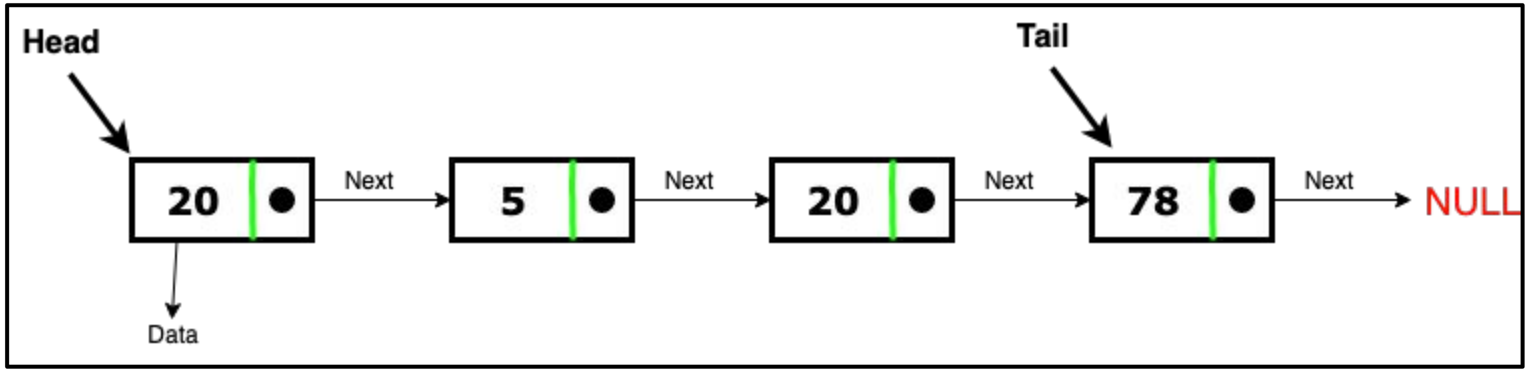


https://dev.to/tastaslim/an-introduction-to-linked-list-1bmp

Linked List Overview

The first element is often called “**head**”

The last element is often called “**tail**”



Node

Linked List

```
static class Node{
    int elem;
    Node next;

    public Node(int elem){
        this.elem = elem;
        this.next = null;
    }
}
```

```
private Node head;
```

Linked List Creation

- Create a linked list from these elements: 21, 43, 31, 10

```
Node n1 = new Node( elem: 21);
Node n2 = new Node( elem: 43);
Node n3 = new Node( elem: 31);
Node n4 = new Node( elem: 10);
```

Linked List Creation

- Create a linked list from these elements: 21, 43, 31, 10

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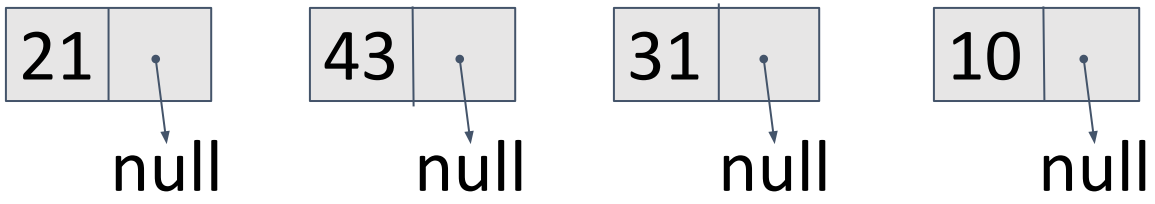

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```
Node n1 = new Node( elem: 21);
Node n2 = new Node( elem: 43);
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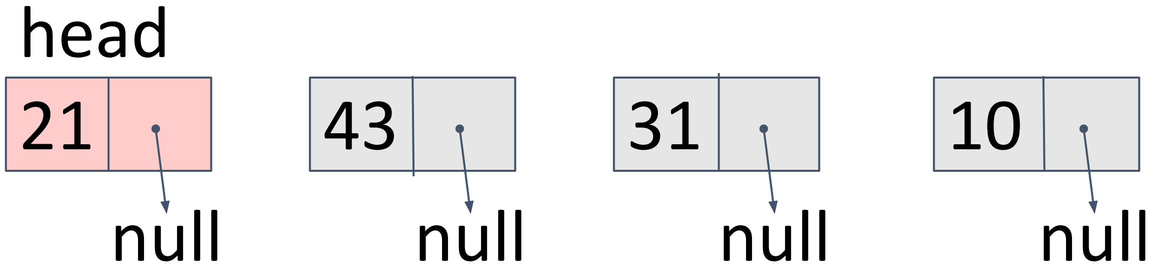
Node n4 = new Node( elem: 10);

Node head = n1;
```



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Node n1 = new Node( elem: 21);
Node n2 = new Node( elem: 43);
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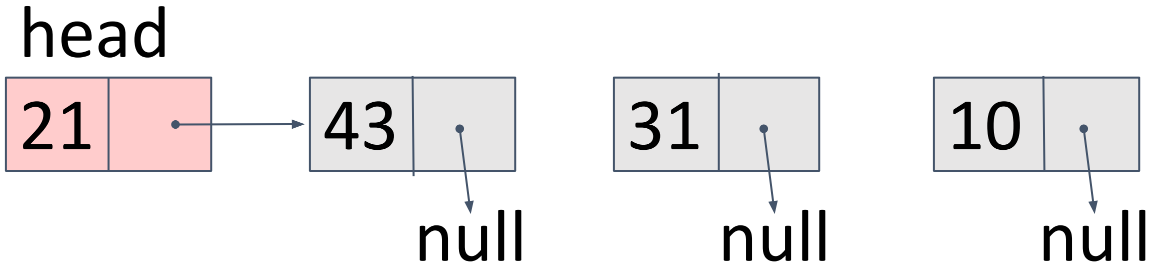
Node n4 = new Node( elem: 10);

Node head = n1;
n1.next = n2;
```



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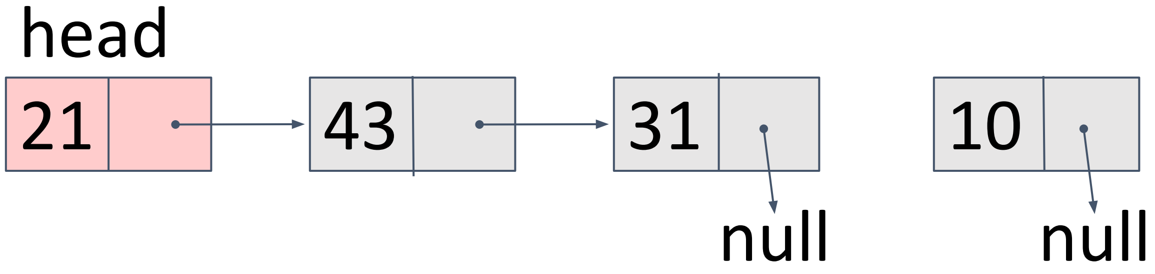
Node n3 = new Node( elem: 31);
Node n4 = new Node( elem: 10);

Node head = n1;
n1.next = n2;
n2.next = n3;
```



Linked List Creation

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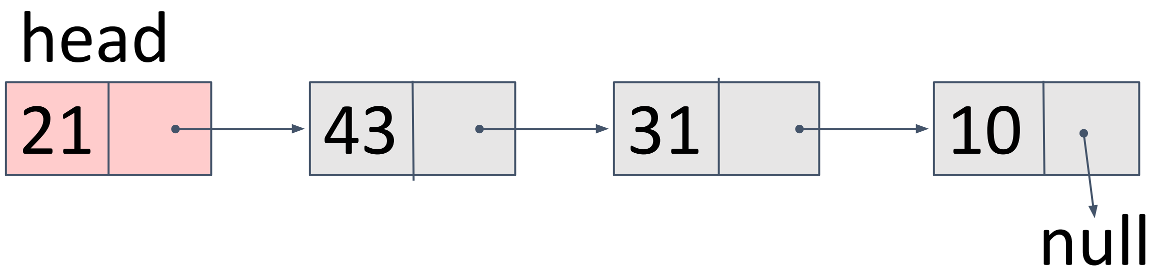
n2.next = n3;
n3.next = n4;
```



Linked List Creation

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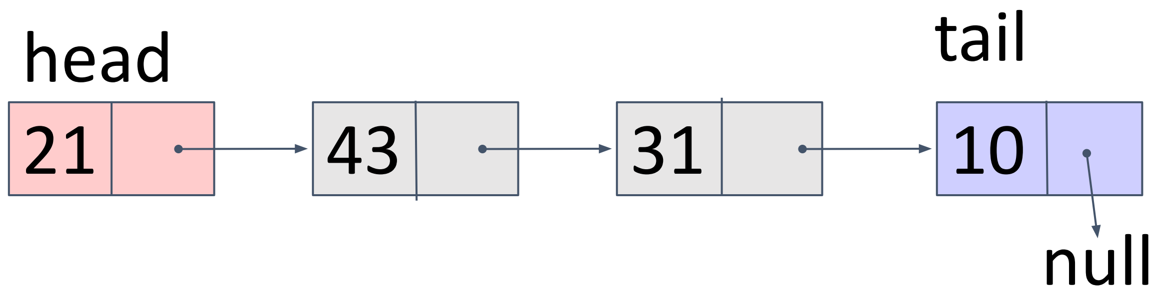
```
Node n1 = new Node( elem: 21);
Node n2 = new Node( elem: 43);
Node n3 = new Node( elem: 31);
Node n4 = new Node( elem: 10);

Node head = n1;
n1.next = n2;
n2.next = n3;
n3.next = n4;
Node tail = n4;
```



Linked List Creation

- Create a linked list from an array

arr = [21, 43, 31, 10]

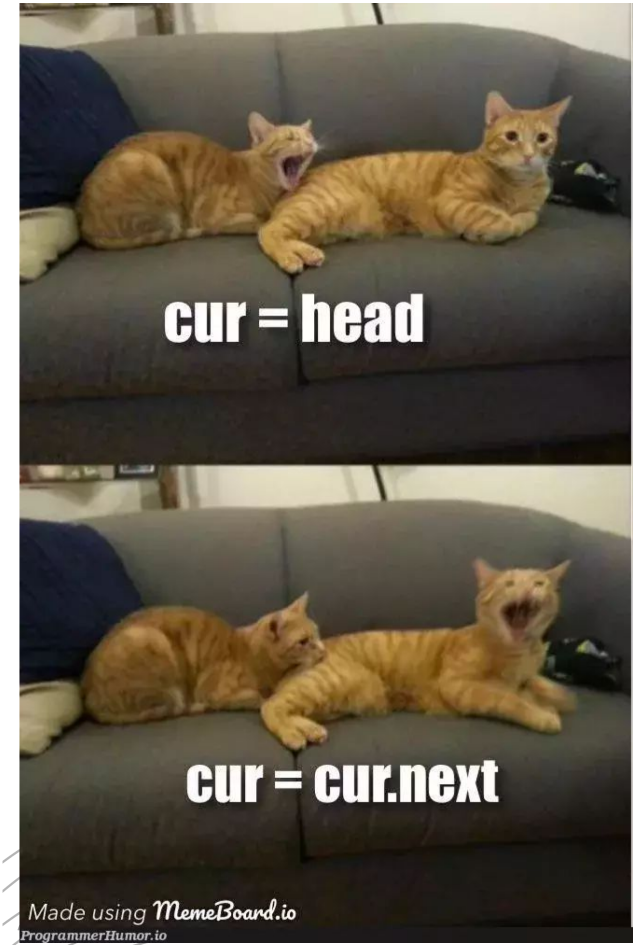
```java
// 1. Create a Linked List from an array
public void createFromArray(int[] arr) {
    if (arr == null || arr.length == 0) return;
    head = new Node(arr[0]);
    Node current = head;
    for (int i = 1; i < arr.length; i++) {
        current.next = new Node(arr[i]);
        current = current.next;
    }
}
```

$O(n)$

Linked List Creation

- Create a linked list from an array

arr = [21, 43, 31, 10]

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public void createFromArray(int[] arr) {
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    head = new Node(arr[0]);
    Node current = head;
    for (int i = 1; i < arr.length; i++) {
        current.next = new Node(arr[i]);
        current = current.next;
    }
}
```

$$O(n)$$

Sequential Traversal

```java
// 2. Iteration of the linked list
public void iterate() {
    Node current = head;
    while (current != null) {
        System.out.print(current.elem + " -> ");
        current = current.next;
    }
    System.out.println();
}
```

$O(n)$

Output: **21->43->31->10->**

Think: Why did we need a “current” node?

Element Access

```java
// 4. Retrieve index of an element
public int indexOf(int elem) {
    int index = 0;
    Node current = head;
    while (current != null) {
        if (current.elem == elem) {
            return index;
        }
        current = current.next;
        index++;
    }
    return -1; // Element not found
}
```

$$O(n)$$

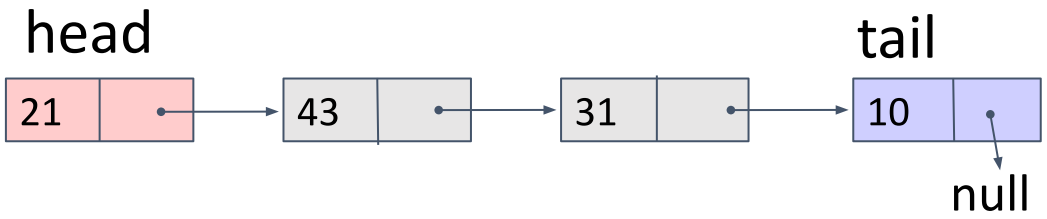
```java
// 5. Retrieve a node from an index
public Node getNode(int index) {
    int currentIndex = 0;
    Node current = head;
    while (current != null) {
        if (currentIndex == index) {
            return current;
        }
        current = current.next;
        currentIndex++;
    }
    return null; // Index out of bounds
}
```

$$O(n)$$

Element Insertion (At the beginning)

- Prepend 99 to the list

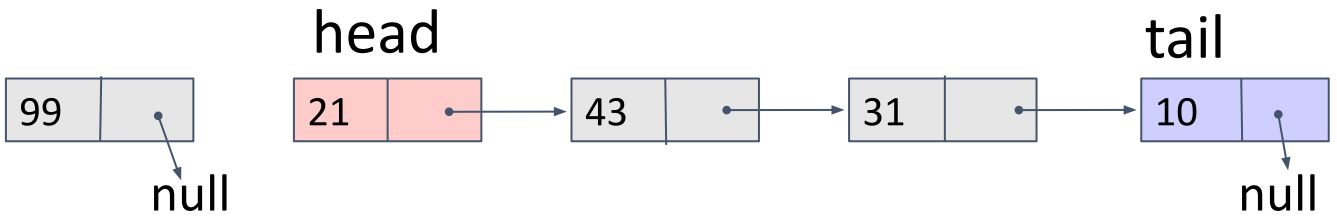
```
// insert at beginning
```



Element Insertion (At the beginning)

- Prepend 99 to the list

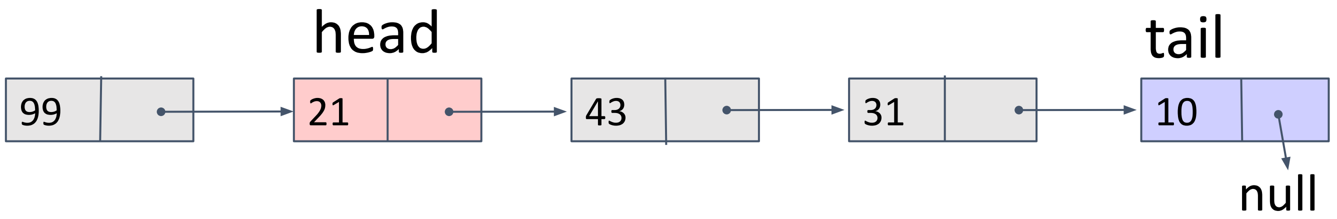
```java
// insert at beginning
Node newNode = new Node( elem: 99);
```



Element Insertion (At the beginning)

- Prepend 99 to the list

```
// insert at beginning
Node newNode = new Node( elem: 99);
newNode.next = head;
```

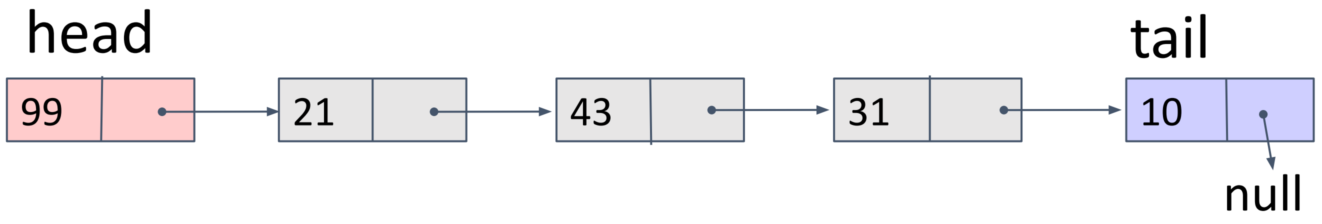


Element Insertion (At the beginning)

- Prepend 99 to the list

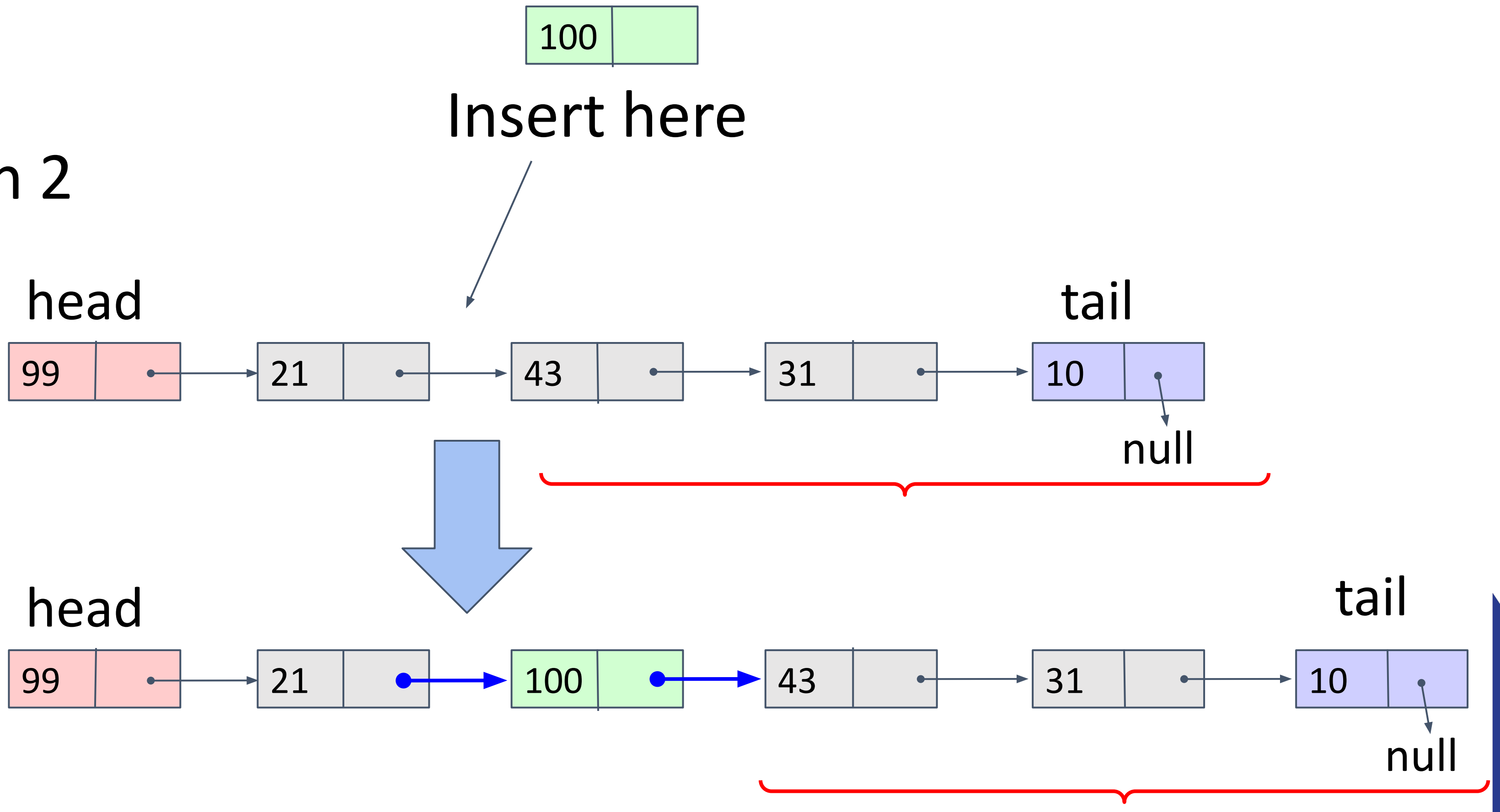
```
// insert at beginning
Node newNode = new Node( elem: 99);
newNode.next = head;
head = newNode;
```

$$O(1)$$



Element Insertion (any position)

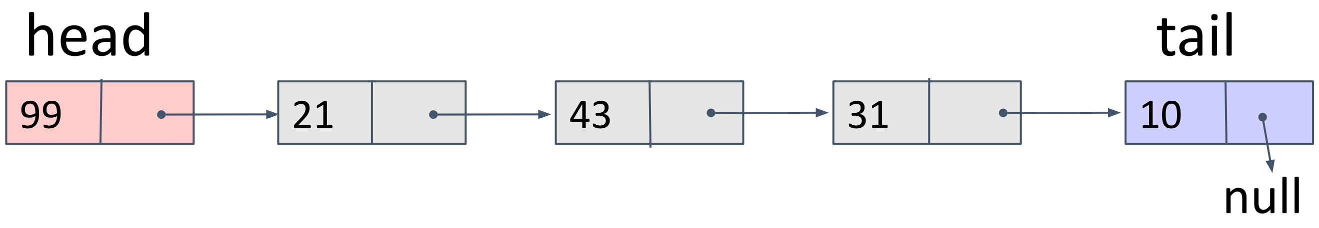
- Insert 100 at position 2



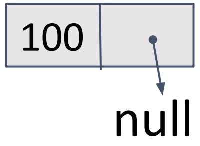

```
Node newNode = new Node(elem);
Node prev = getNode( index: index - 1);
if (prev != null) { // Insert anywhere
    newNode.next = prev.next;
    prev.next = newNode;
}
```

Element Insertion (any position)

- Insert 100 at position 2



Element Insertion (any position)



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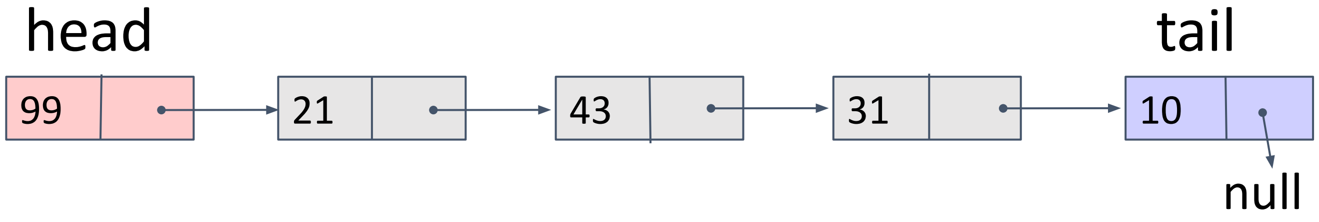
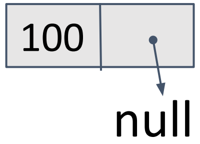



```
Node newNode = new Node(elem);
```

Element Insertion (any position)



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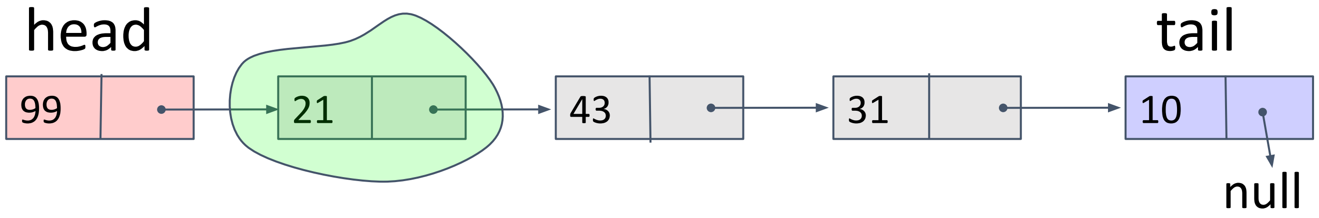
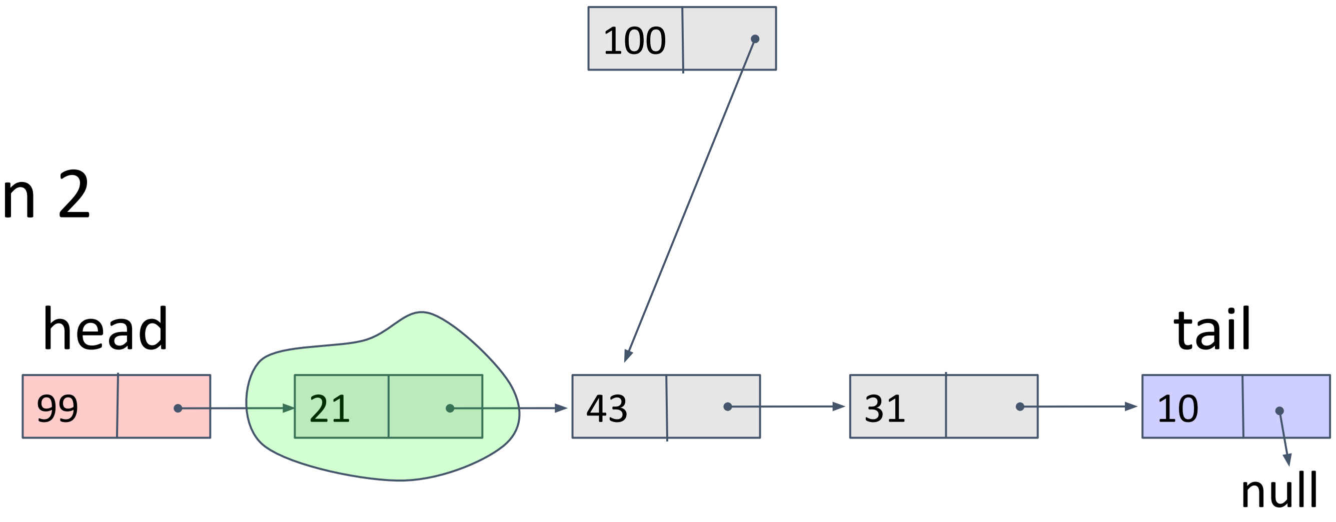



```
Node newNode = new Node(elem);
Node prev = getNode( index: index - 1);
```

Element Insertion (any position)

- Insert 100 at position 2

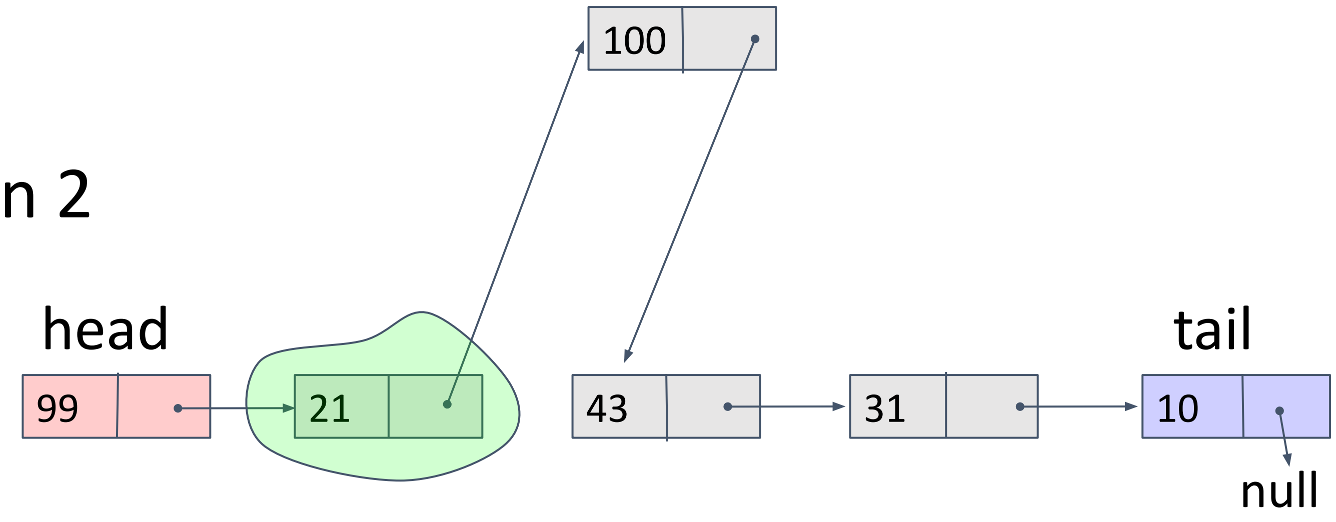



```java
Node newNode = new Node(elem);
Node prev = getNode( index: index - 1);

    newNode.next = prev.next;
```

Element Insertion (any position)

- Insert 100 at position 2




```
Node newNode = new Node(elem);
Node prev = getNode( index: index - 1);

    newNode.next = prev.next;
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```

Element Insertion (any position)

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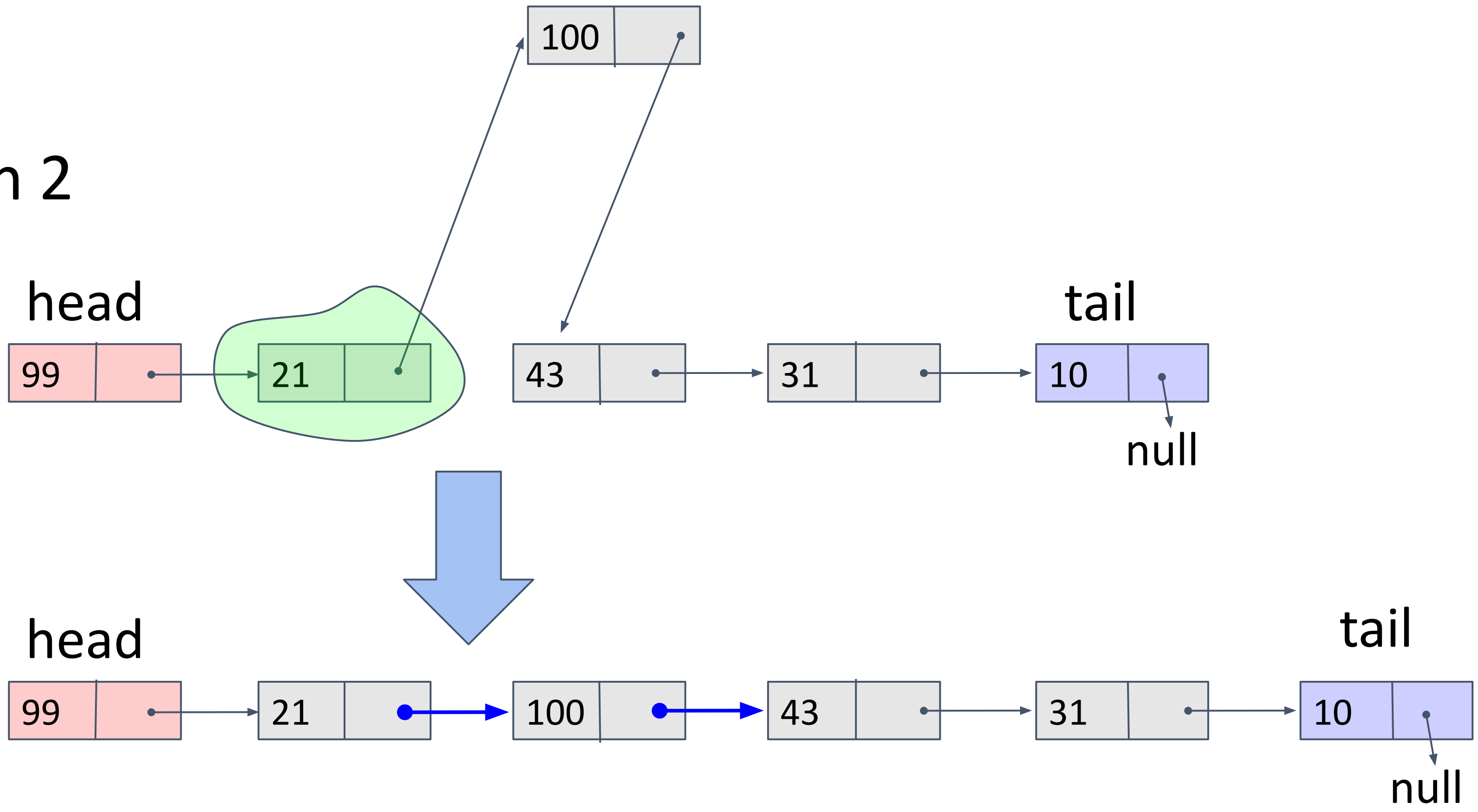


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Element Insertion (any position)

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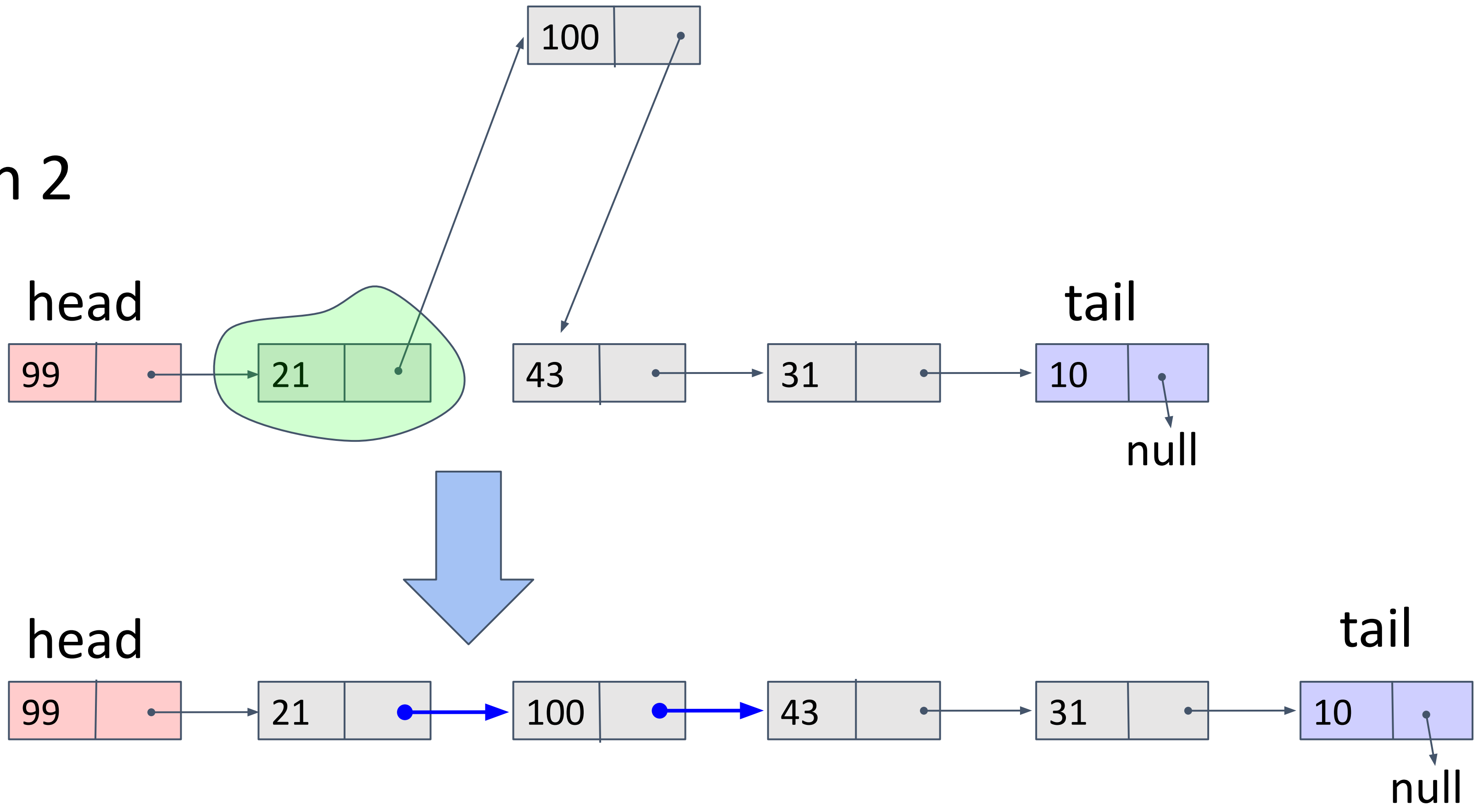
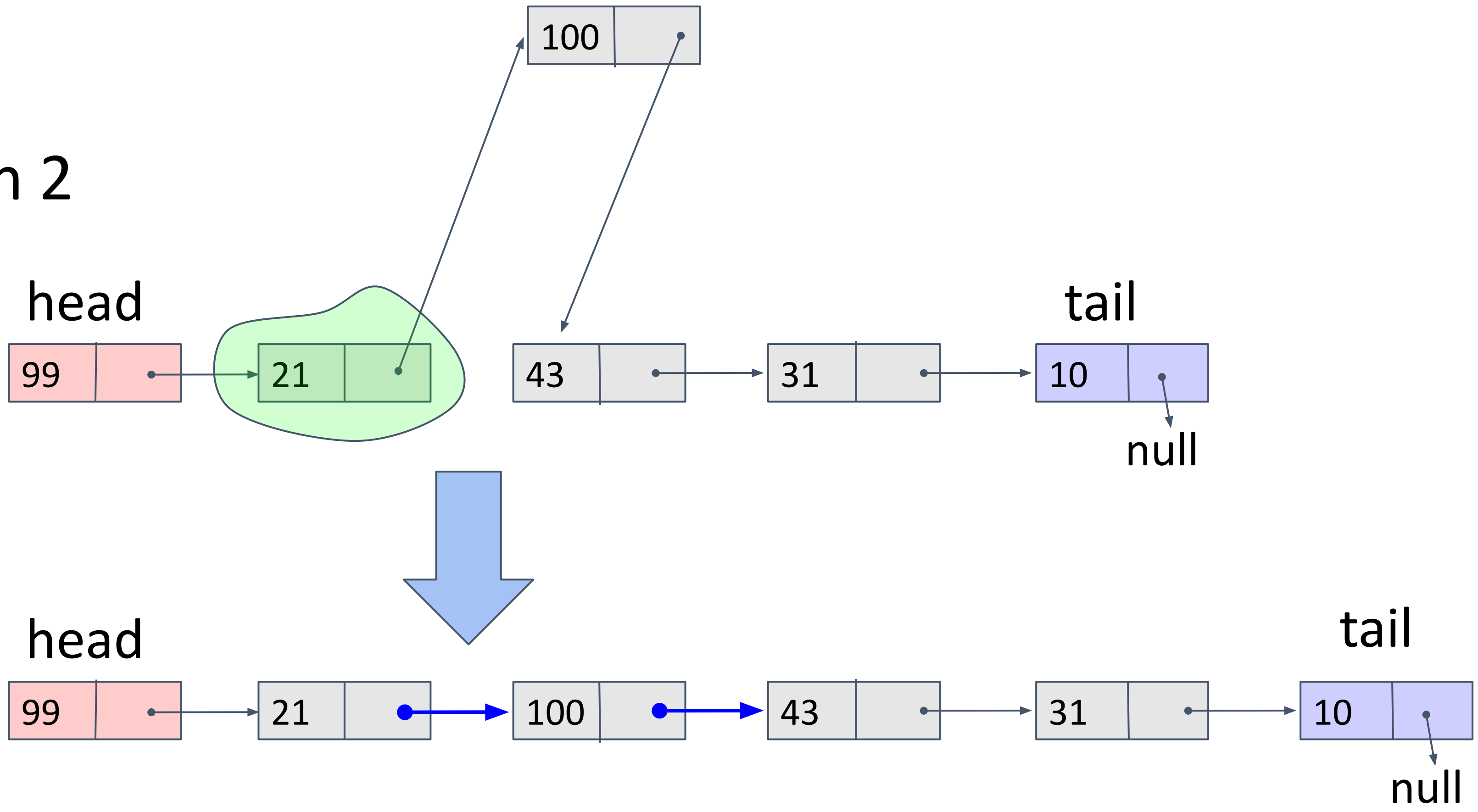


$O(n)$

```java
Node newNode = new Node(elem);
Node prev = getNode( index: index - 1);
if (prev != null) { // Cannot insert before head
    newNode.next = prev.next;
    prev.next = newNode;
}
```

Element Insertion (any position)

- Insert 100 at position 2



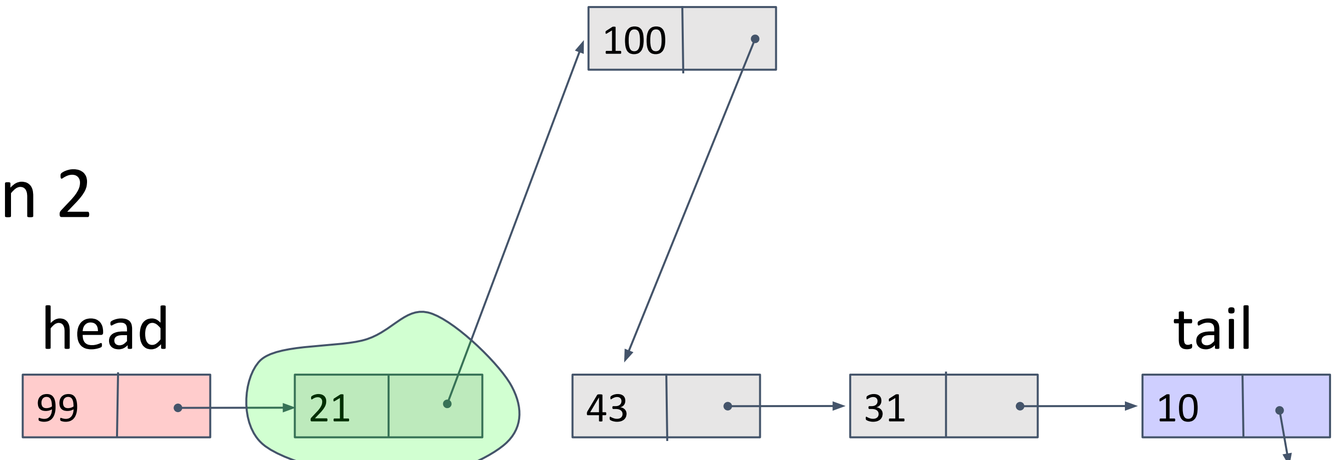
$O(n)$

```
Node newNode = new Node(elem);
Node prev = getNode( index: index - 1);
if (prev != null) { // Cannot insert before head
    newNode.next = prev.next;
    prev.next = newNode;
}
```

Ordering is important!

Element Insertion (any position)

- Insert 100 at position 2



$$O(n)$$

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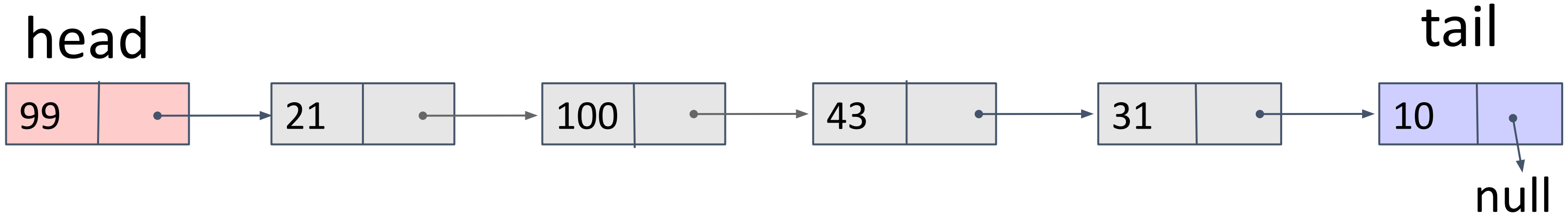
}
```

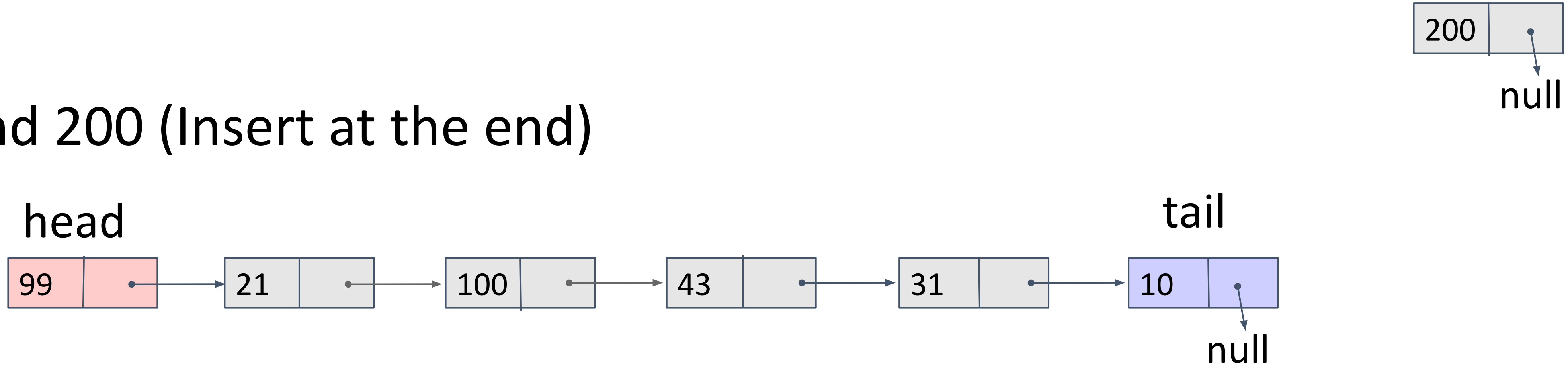
Optimizing Tail Insertion

- Append 200 (Insert at the end)



Optimizing Tail Insertion

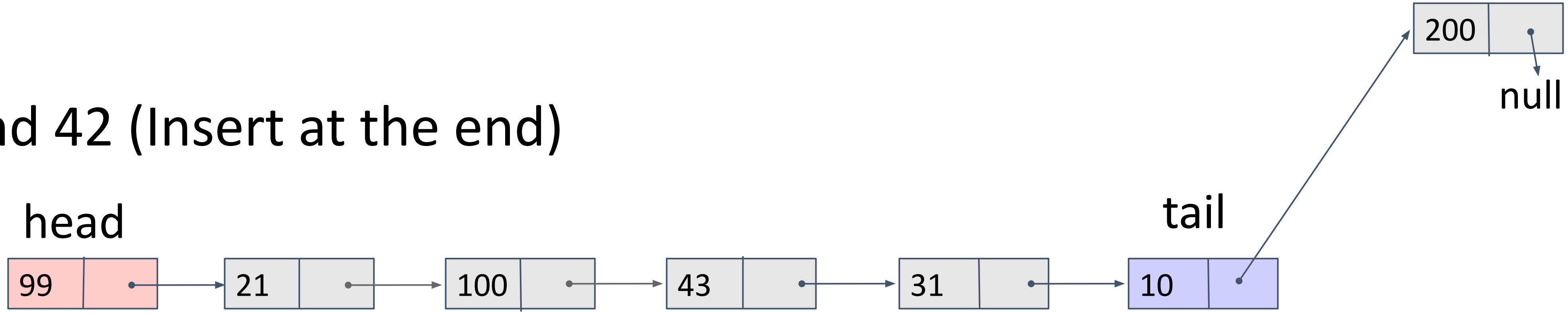
- Append 200 (Insert at the end)




```
Node newNode = new Node( elem: 200);
```

Optimizing Tail Insertion

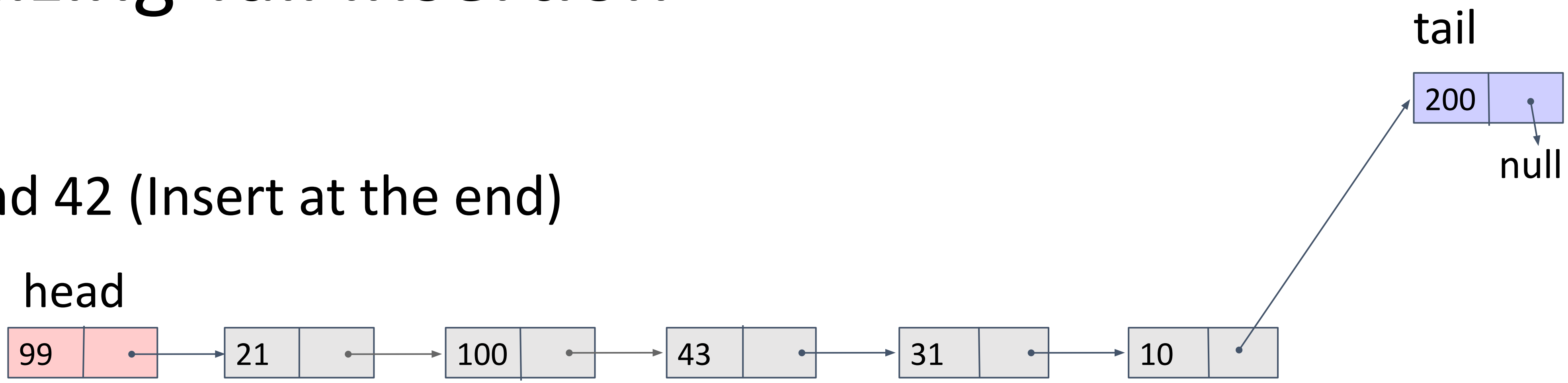
- Append 42 (Insert at the end)




```
Node newNode = new Node( elem: 200);
tail.next = newNode;
```

Optimizing Tail Insertion

- Append 42 (Insert at the end)

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Node newNode = new Node( elem: 200);
tail.next = newNode;
tail = newNode;
```
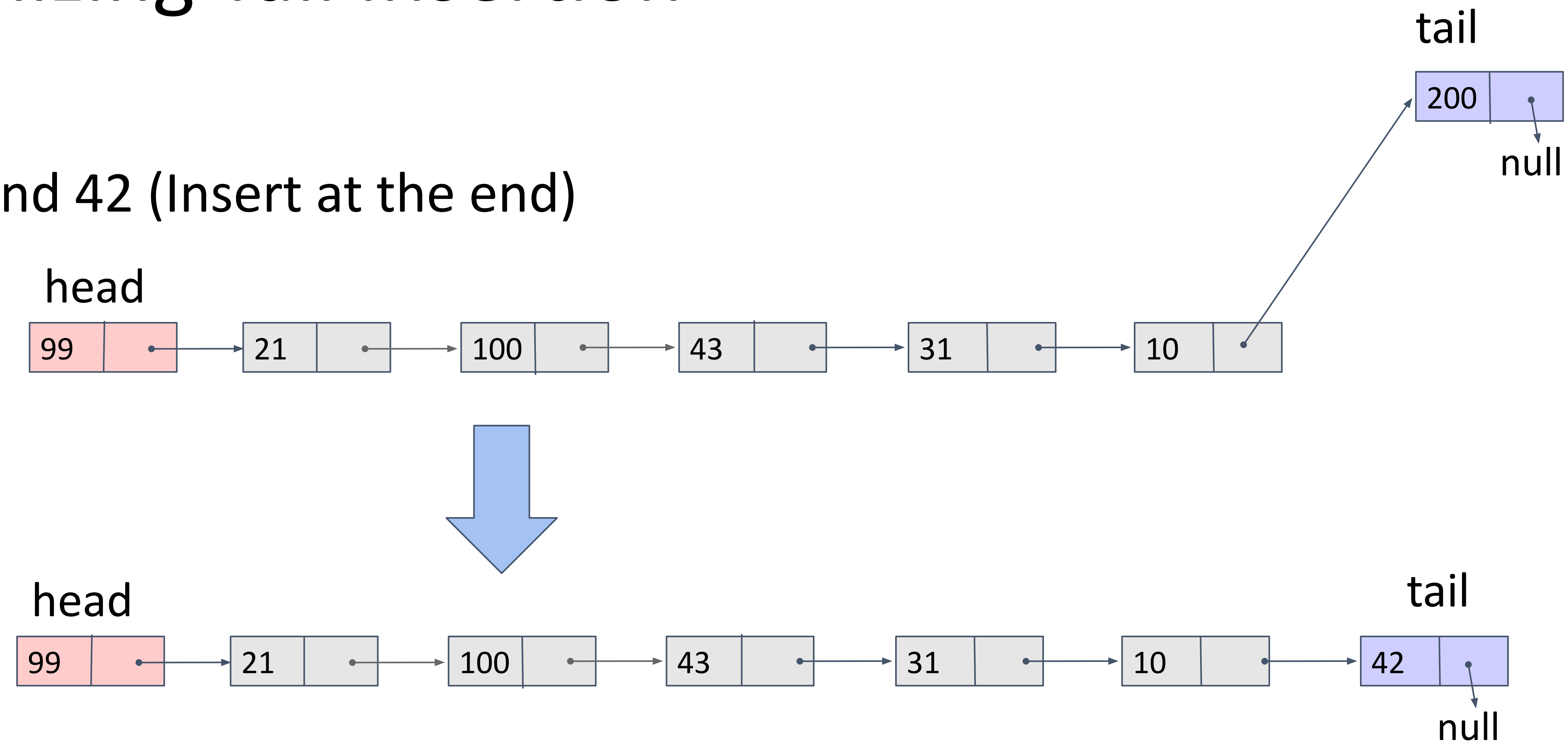

Optimizing Tail Insertion

- Append 42 (Insert at the end)




```java
Node newNode = new Node( elem: 200);
tail.next = newNode;
tail = newNode;
```

$O(1)$

When to Use Linked Lists?

- Use linked lists:
  - When you need frequent insertions/deletions (e.g., implementing a queue or stack).
  - When the size of the data is unknown or changes frequently.
- Do not use linked lists:
  - Random access is needed (Arrays $\Rightarrow$ O(1), Linked lists $\Rightarrow$ O(n))
- Practical usage:
  - In xv6, the freelist refers to a linked list of free memory pages
  - Each free page contains a pointer to the next free page.

Exercise

- Remove head
- Remove tail
- Remove from anywhere
- Update element value at index n