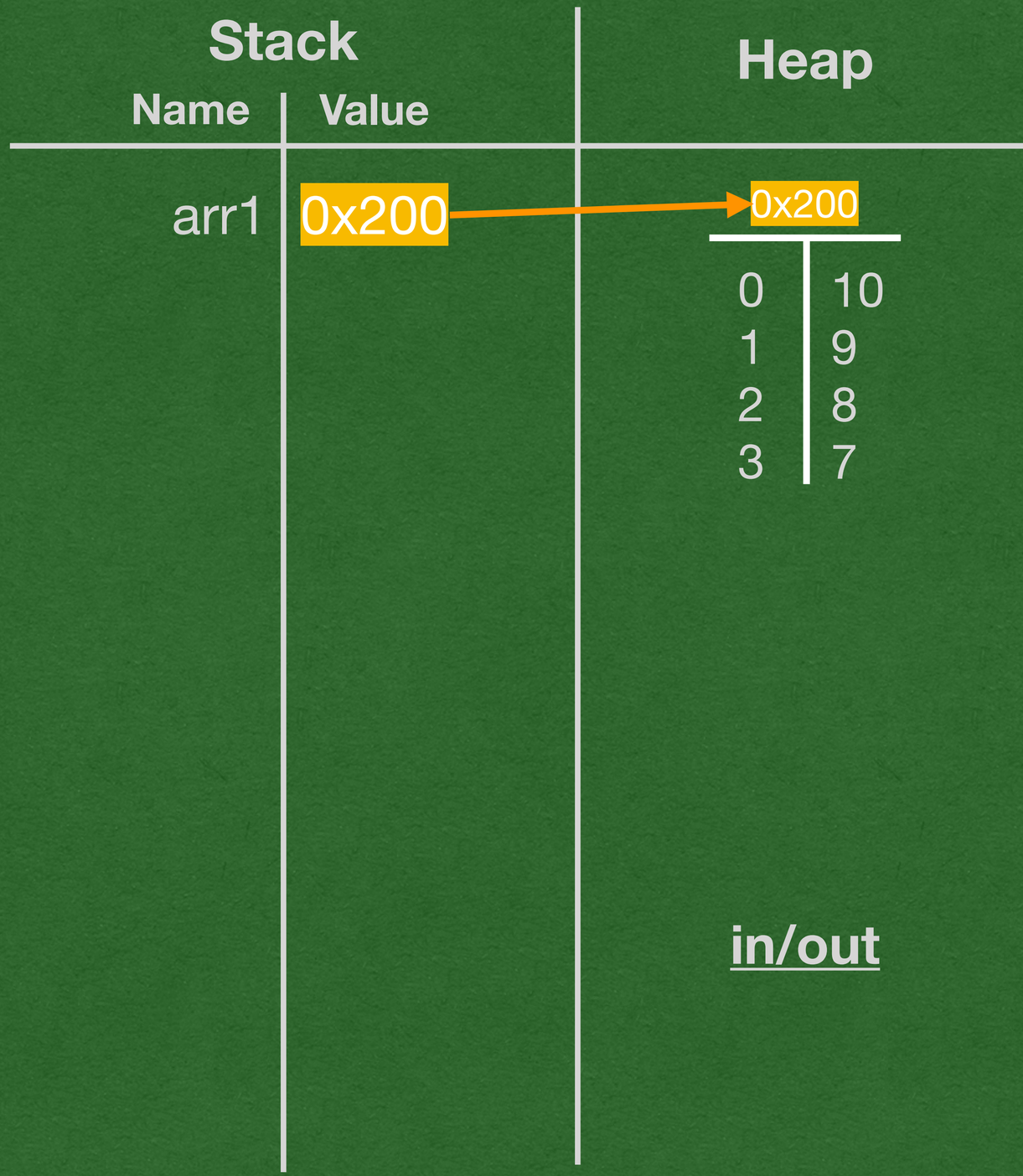
Linked List

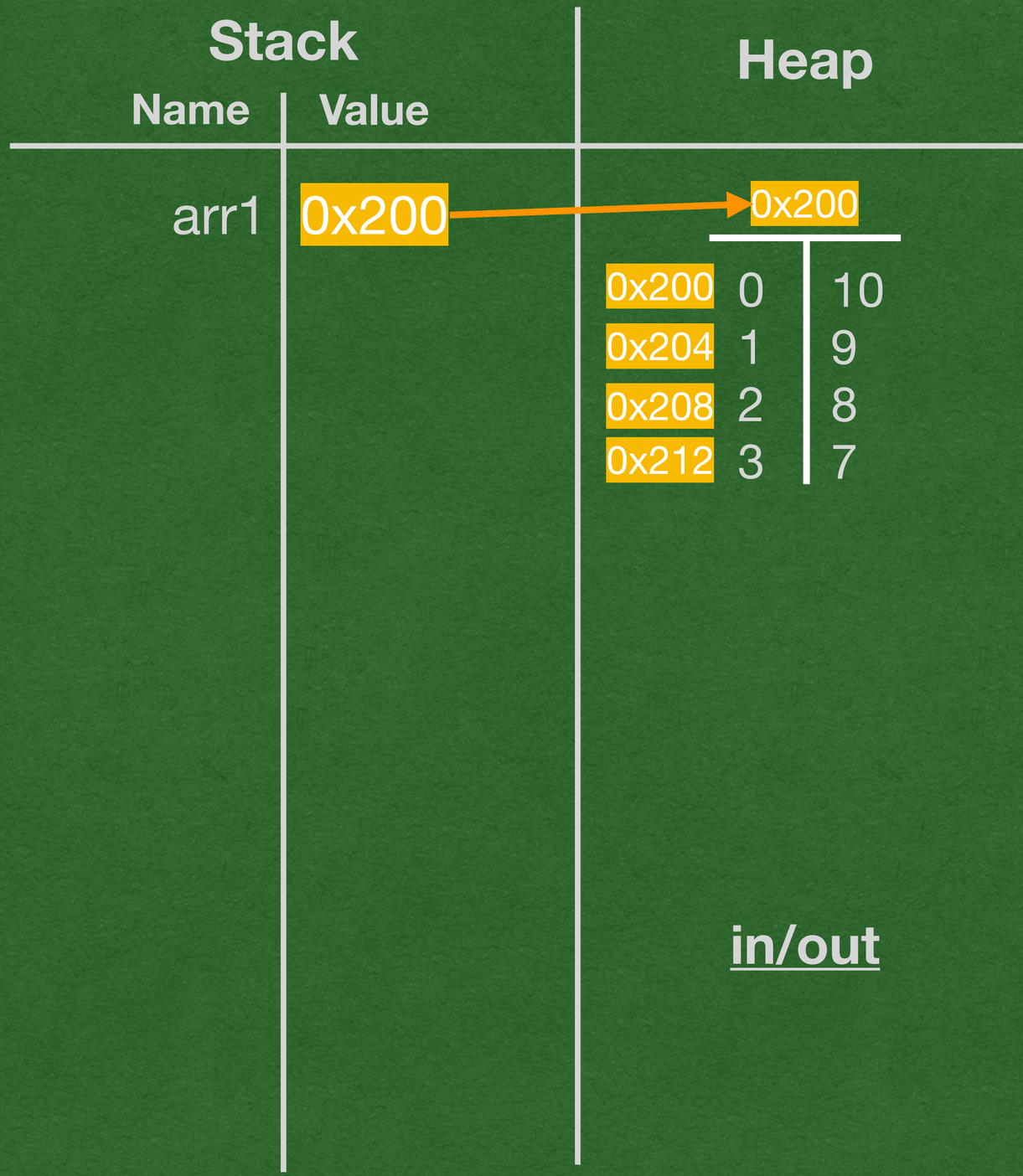
ArrayList [And Array]

- Sequential
  - One continuous block of memory
  - Random access based on memory address
    - address = first_address + (element_size * index)
- Fixed Size
  - Since memory adjacent to the block may be used
  - Efficient when you know how many elements you'll need to store

- We show an ArrayList on the heap in columns
- Values are all located in one continuous block of memory
- This is actually how ArrayLists [and Arrays] are stored



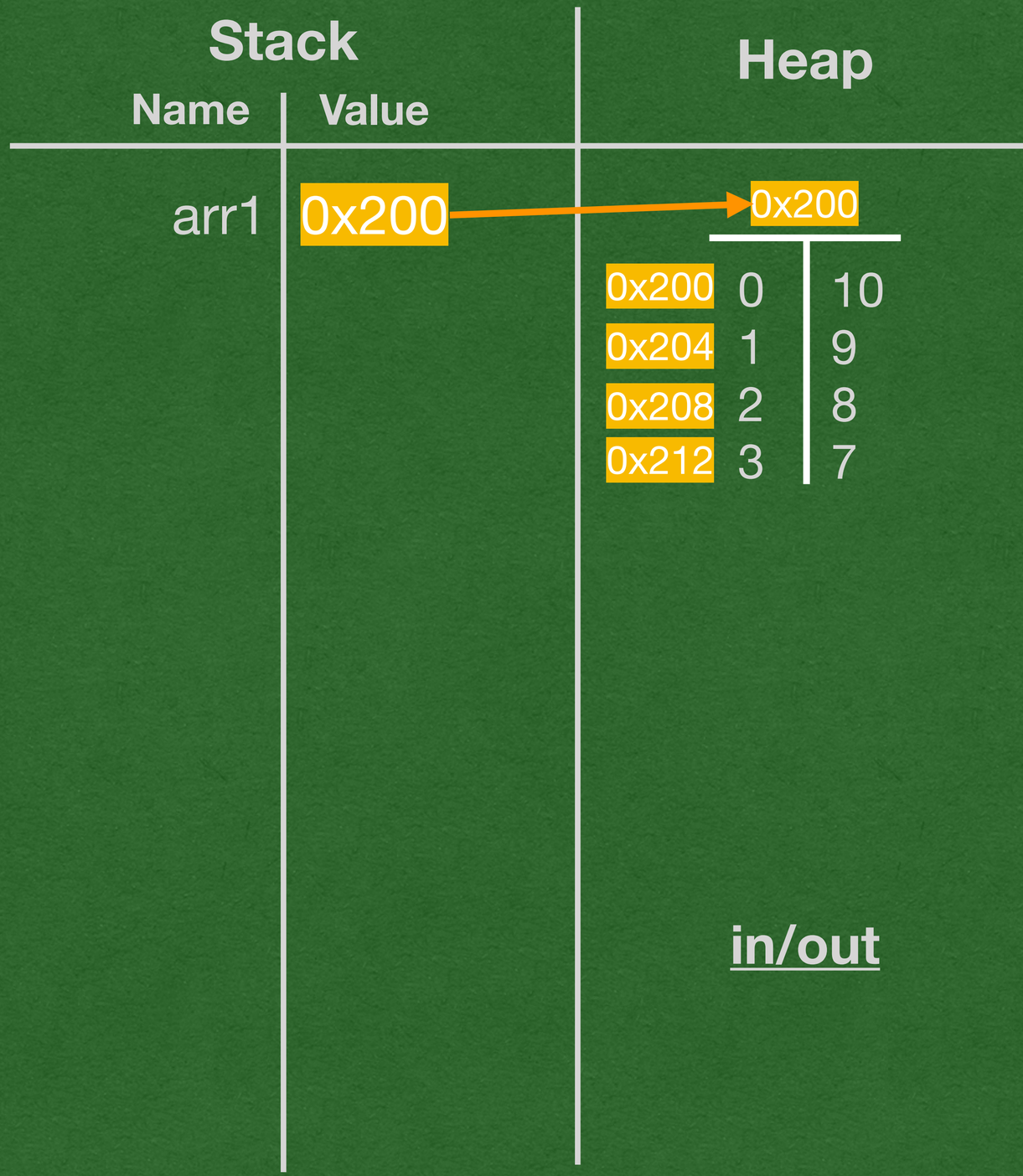
in/out



- This ArrayList stores 32-bit ints (4 bytes) and the ArrayList is stored at memory address 0x200
  - Find the element of each value using
  - address = 0x200 + (4 * index)
- Easy to find any value, given it's index

in/out

- This is called random access
- Memory is like a giant array
  - We call it RAM (Random Access Memory)



in/out

Linked List

- Sequential
  - Spread across memory
  - Each element knows the memory address of the next element
    - Follow the addresses to find each element
- Variable Size
  - Store new element anywhere in memory

Linked List

- Each value in a list is stored in a separate object on the heap
- Also stores a reference to the next element
- A reference to the list is only a reference to the first value
- Last link stores null
  - We say the list is "null terminated"
  - When we read a value of null we know we've reached the end of the list

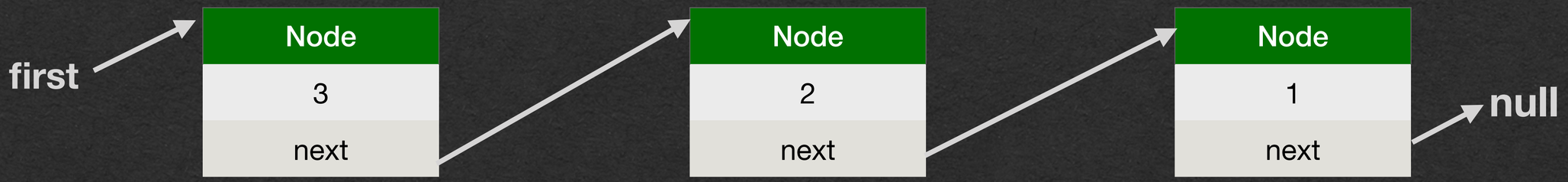
Linked List

```java
package week4;

public class LinkedListNodeInt {
    private int value;
    private LinkedListNodeInt next;

    public LinkedListNodeInt(int value, LinkedListNodeInt next) {
        this.value = value;
        this.next = next;
    }

    public static void main(String[] args) {
        LinkedListNodeInt first = new LinkedListNodeInt(1, null);
        first = new LinkedListNodeInt(2, first);
        first = new LinkedListNodeInt(3, first);
    }
}
```

- We create our own linked list node class
- A node represents one "link" in the list
- The list itself is a reference to the first/head node

Structure

- Each node stores one value of the list
- Each node refers to the next node
- A variable "storing" a list stores a reference to the first node of the list



Memory Diagram

- LinkedListNodeInt -> LLNode
  - To save space on the slide

```
public class LLNode {
    private int value;
    private LLNode next;

    public LLNode(int value, LLNode next) {
        this.value = value;
        this.next = next;
    }

    public static void main(String[] args) {
        LLNode first = new LLNode(1, null);
        first = new LLNode(2, first);
        first = new LLNode(3, first);
    }
}
```

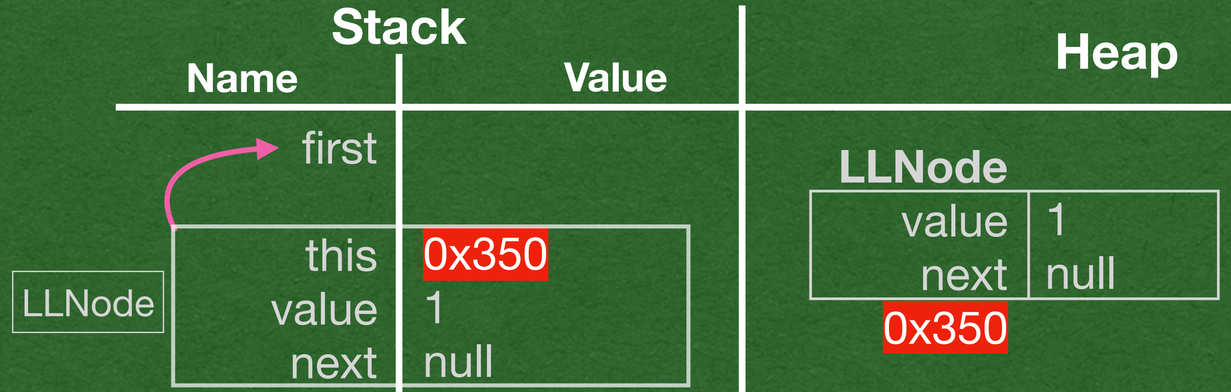
Stack

Name	Value

Heap

in/out

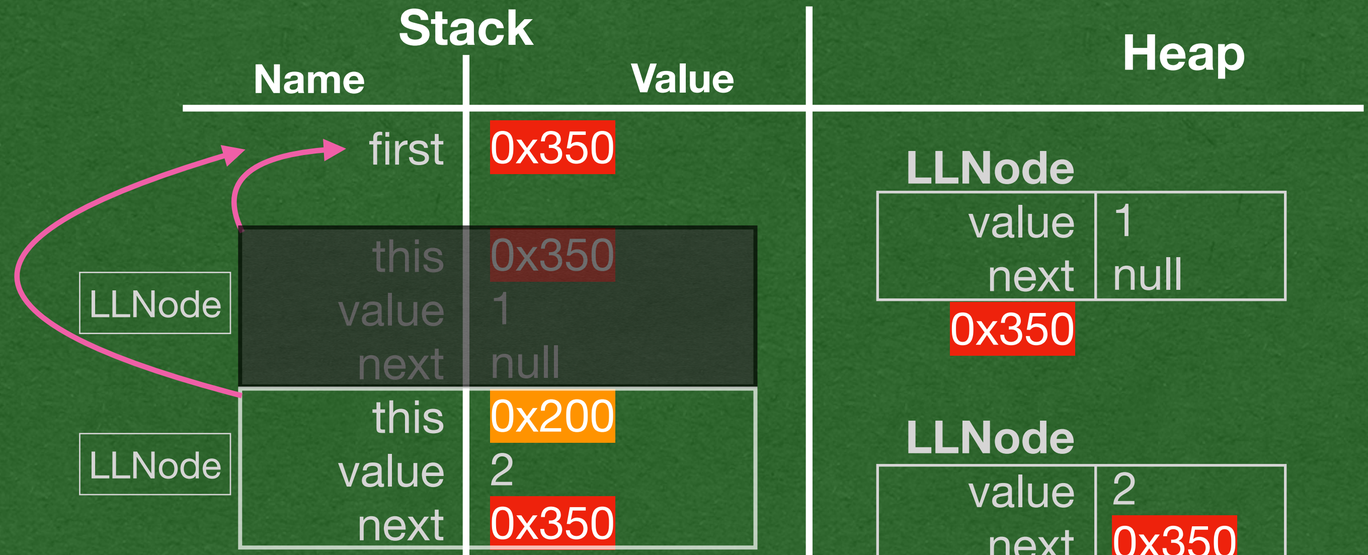
- Create a LLNode object
- next is equal to null
  - The lack of a reference




```java
public class LLNode {
    private int value;
    private LLNode next;

    public LLNode(int value, LLNode next) {
        this.value = value;
        this.next = next;
    }

    public static void main(String[] args) {
        LLNode first = new LLNode(1, null);
        first = new LLNode(2, first);
        first = new LLNode(3, first);
    }
}
```

in/out

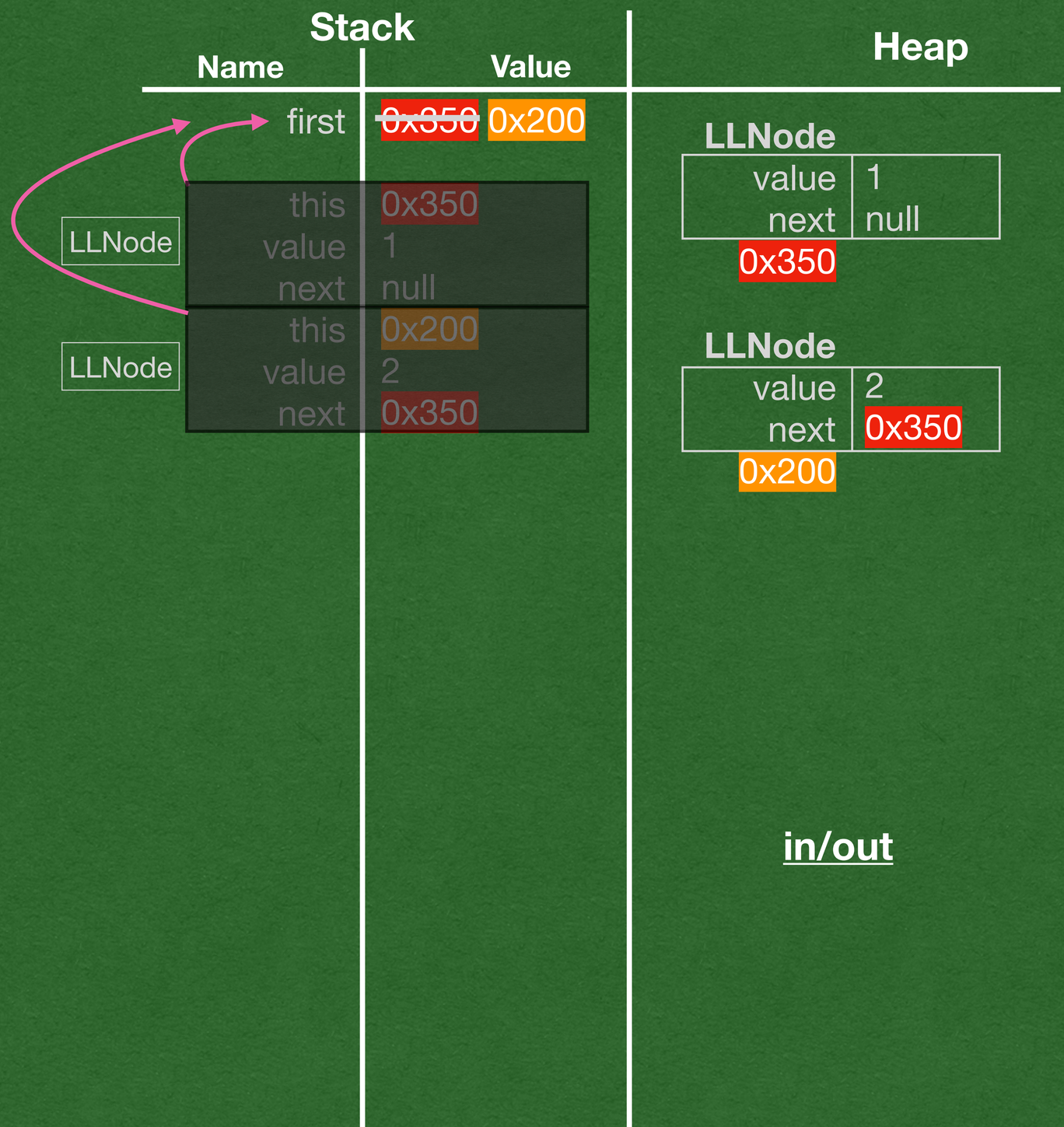
- Call the constructor again
- Pass myList (0x350) as next




```java
public class LLNode {
    private int value;
    private LLNode next;

    public LLNode(int value, LLNode next) {
        this.value = value;
        this.next = next;
    }

    public static void main(String[] args) {
        LLNode first = new LLNode(1, null);
        first = new LLNode(2, first);
        first = new LLNode(3, first);
    }
}
```

in/out

- Reassign first to the reference returned by the constructor
- first now stores 0x200 which has a next of 0x350



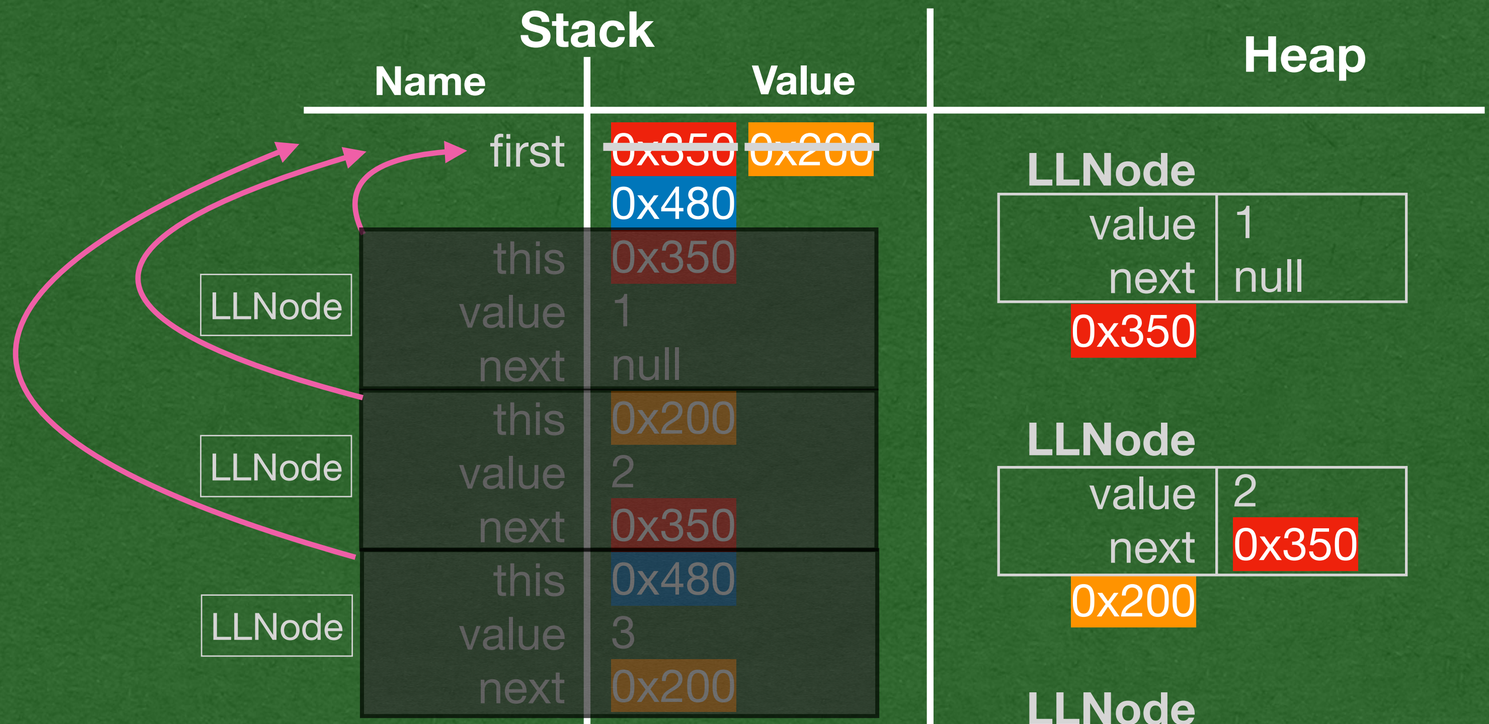

```java
public class LLNode {
    private int value;
    private LLNode next;

    public LLNode(int value, LLNode next) {
        this.value = value;
        this.next = next;
    }

    public static void main(String[] args) {
        LLNode first = new LLNode(1, null);
        first = new LLNode(2, first);
        first = new LLNode(3, first);
    }
}
```

in/out

- Repeat the process for the node with value 3
- We now have a linked list with 3 elements


```
public class LLNode {
    private int value;
    private LLNode next;

    public LLNode(int value, LLNode next) {
        this.value = value;
        this.next = next;
    }

    public static void main(String[] args) {
        LLNode first = new LLNode(1, null);
        first = new LLNode(2, first);
        first = new LLNode(3, first);
    }
}
```

- Our variable "first" only stores a reference to the first node of the list
- We call the first node the head of the list




```
public class LLNode {
    private int value;
    private LLNode next;

    public LLNode(int value, LLNode next) {
        this.value = value;
        this.next = next;
    }

    public static void main(String[] args) {
        LLNode first = new LLNode(1, null);
        first = new LLNode(2, first);
        first = new LLNode(3, first);
    }
}
```

in/out

- Each node stores one value of the list and a reference to the next node
- Each node can be anywhere on the heap

```
public class LLNode {
    private int value;
    private LLNode next;

    public LLNode(int value, LLNode next) {
        this.value = value;
        this.next = next;
    }

    public static void main(String[] args) {
        LLNode first = new LLNode(1, null);
        first = new LLNode(2, first);
        first = new LLNode(3, first);
    }
}
```

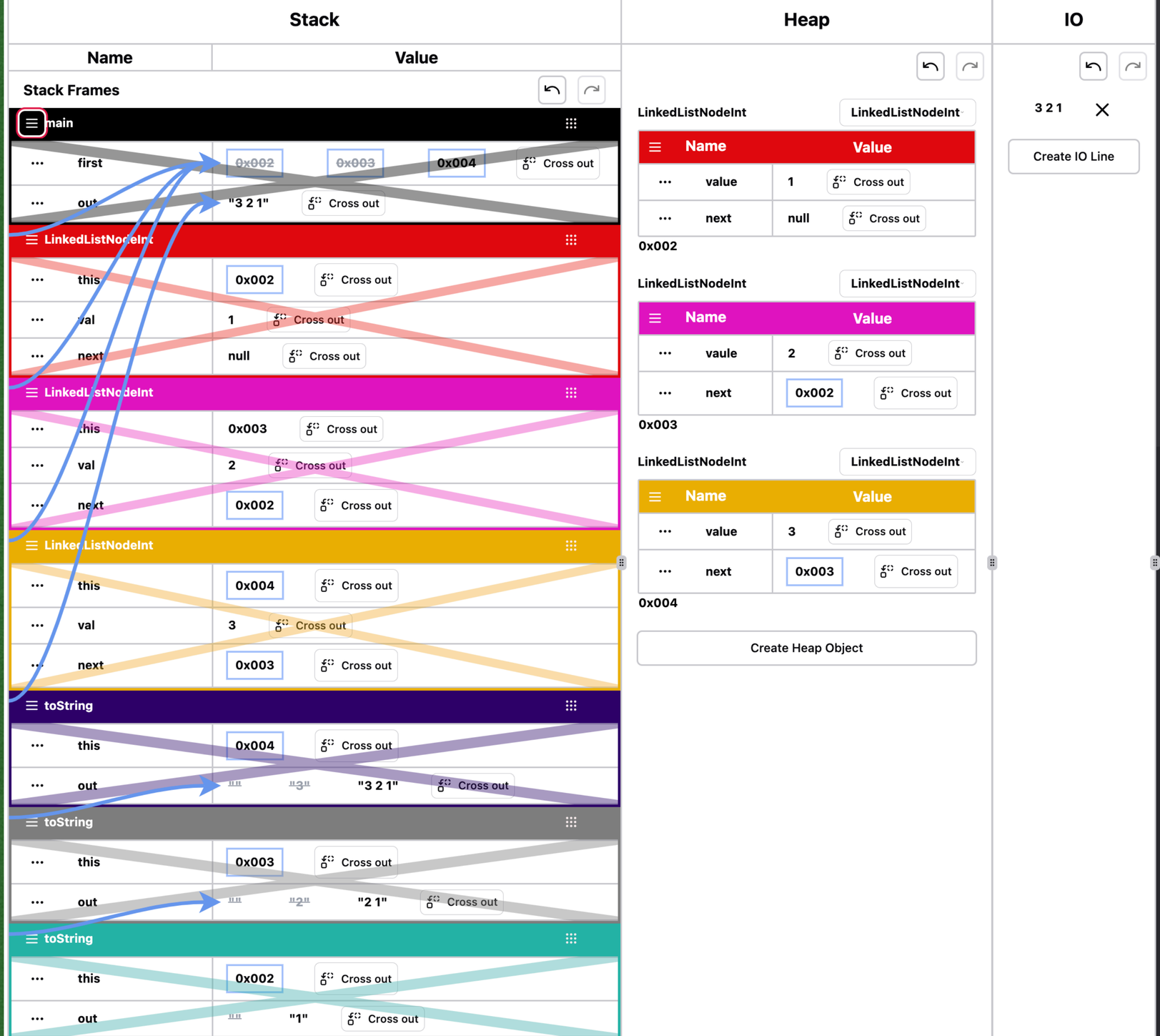
toString

```
public class LLNode {
    private int value;
    private LLNode next;

    public LLNode(int val, LLNode next) {
        this.value = val;
        this.next = next;
    }

    public String toString() {
        String out = "";
        out += this.value;
        if (this.next != null) {
            out += " " + this.next.toString();
        }
        return out;
    }

    public static void main(String[] args) {
        LLNode first = new LLNode(1, null);
        first = new LLNode(2, first);
        first = new LLNode(3, first);
        String value = first.toString();
        System.out.println(value);
    }
}
```

- Let's add a toString method to our Linked List
- This will return the values separated by spaces

- .. aaand it uses recursion!
  - Remember recursion?
  - We're using it!

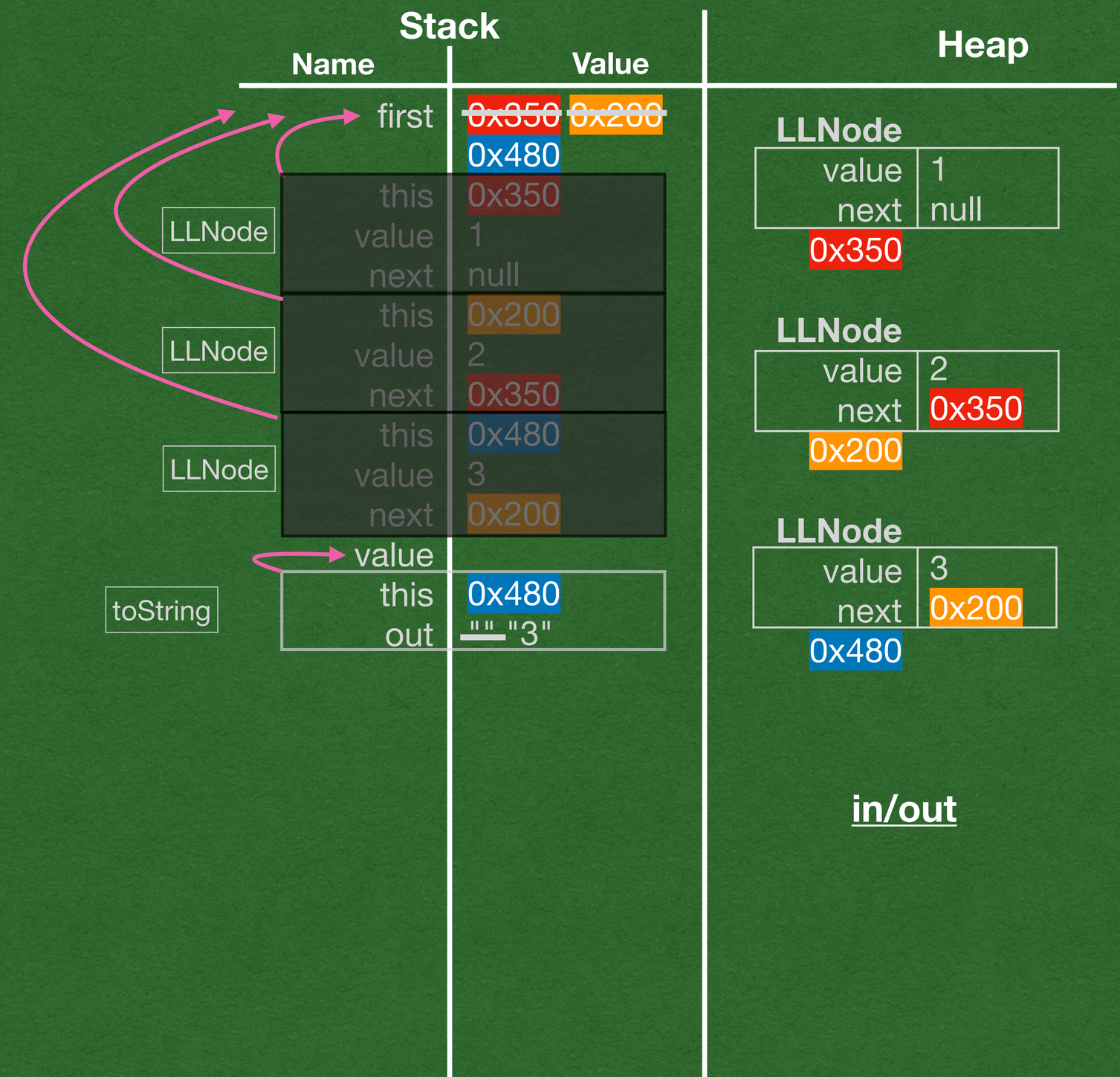
2 Memory 2 Diagram




```java
package week5;

public class LinkedListNodeInt {
    private int value;
    private LinkedListNodeInt next;

    public LinkedListNodeInt(int val, LinkedListNodeInt next) {
        this.value = val;
        this.next = next;
    }

    public String toString() {
        String out = "";
        out += this.value;
        if (this.next != null) {
            out += " " + this.next.toString();
        }
        return out;
    }

    public static void main(String[] args) {
        LinkedListNodeInt first = new LinkedListNodeInt(1, null);
        first = new LinkedListNode<>(2, first);
        first = new LinkedListNode<>(3, first);
        String out = first.toString();
        System.out.println(out);
    }
}

```

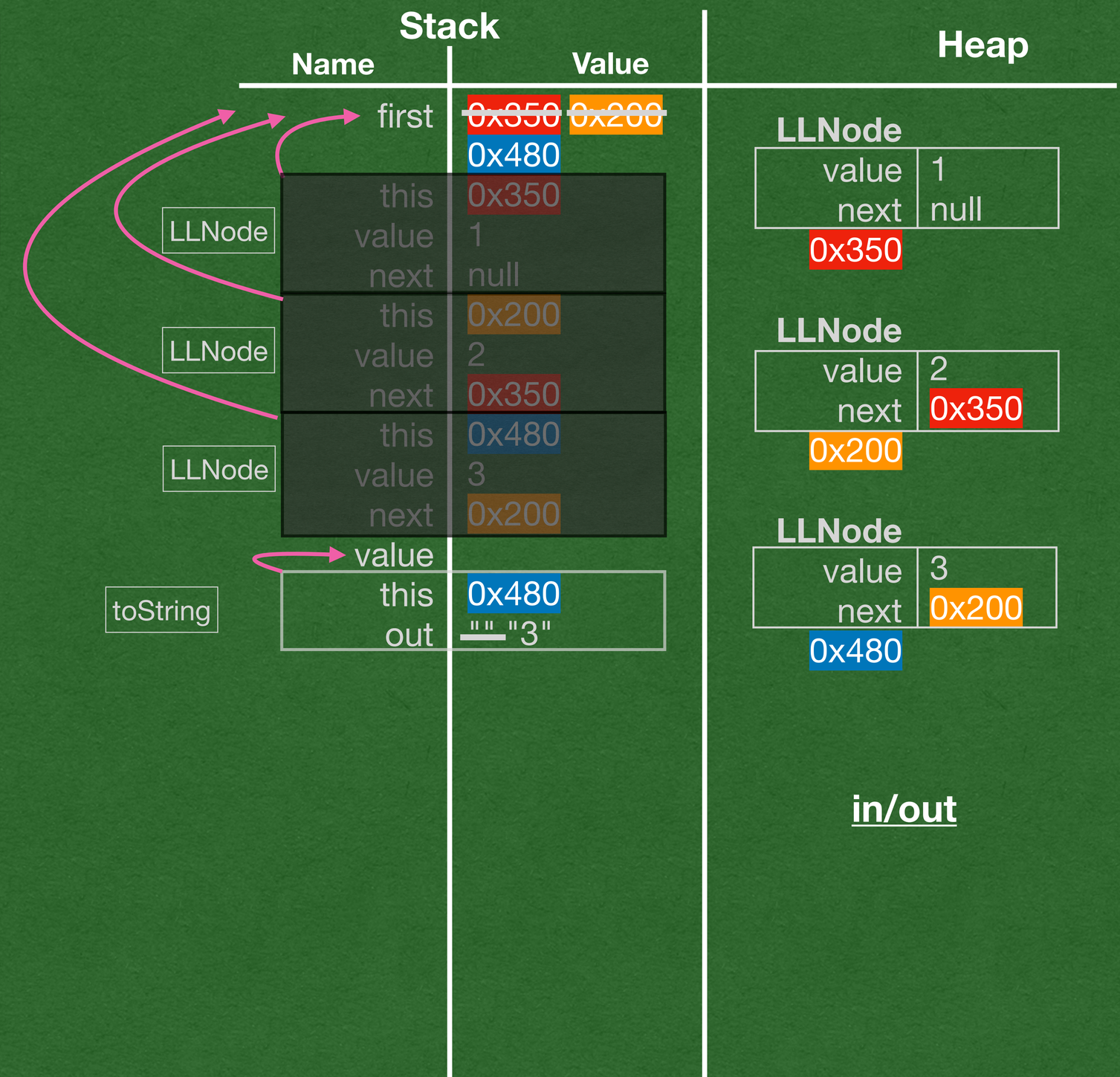
- We could write
  - System.out.println(first)
- We're explicitly calling toString to be clear of our intentions

```
public class LLNode {
    private int value;
    private LLNode next;

    public LLNode(int value, LLNode next) {
        this.value = value;
        this.next = next;
    }

    public String toString() {
        String out = "";
        out += this.value;
        if (this.next != null) {
            out += " " + this.next.toString();
        }
        return out;
    }

    public static void main(String[] args) {
        LLNode first = new LLNode(1, null);
        first = new LLNode(2, first);
        first = new LLNode(3, first);
        String value = first.toString();
        System.out.println(value);
    }
}
```



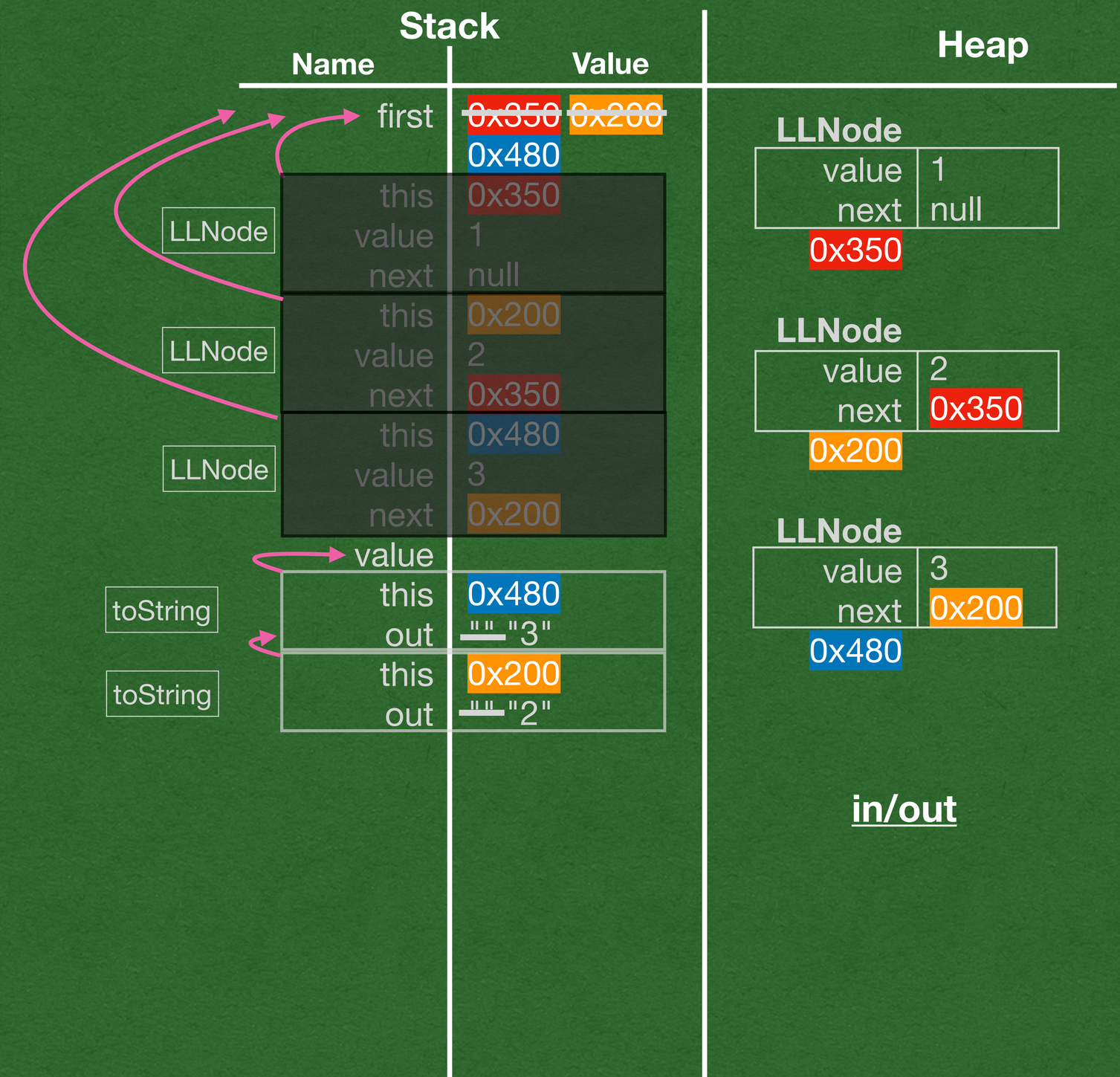
- If next is not null, we are not at the end of the list
  - There's more work to be to done
  - Make a recursive call

```
public class LLNode {
    private int value;
    private LLNode next;

    public LLNode(int value, LLNode next) {
        this.value = value;
        this.next = next;
    }

    public String toString() {
        String out = "";
        out += this.value;
        if (this.next != null) {
            out += " " + this.next.toString();
        }
        return out;
    }

    public static void main(String[] args) {
        LLNode first = new LLNode(1, null);
        first = new LLNode(2, first);
        first = new LLNode(3, first);
        String value = first.toString();
        System.out.println(value);
    }
}
```



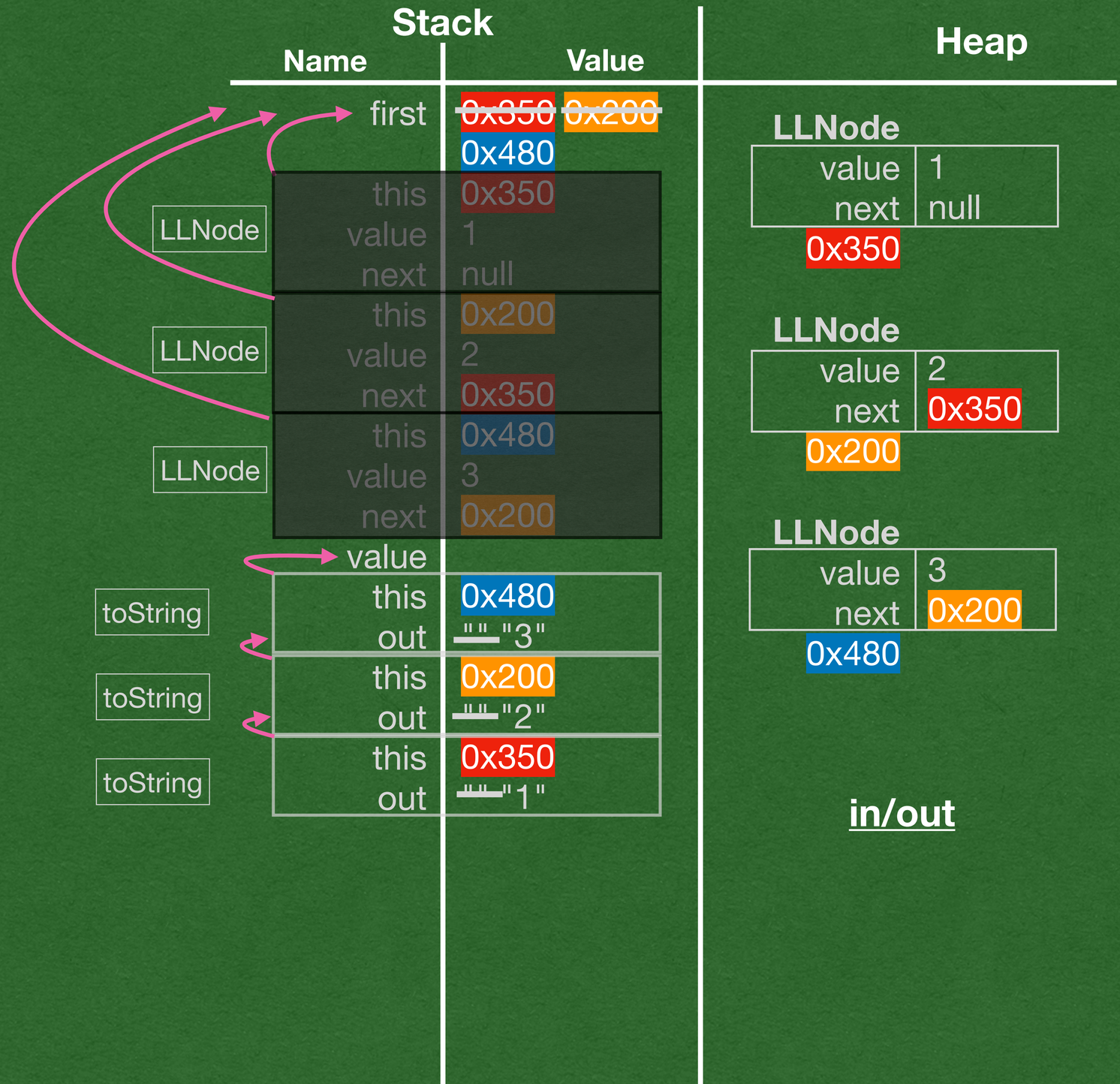
- The recursive call is made on the next node
- The first stack frame waits for the return value of the recursive call

```java
public class LLNode {
    private int value;
    private LLNode next;

    public LLNode(int value, LLNode next) {
        this.value = value;
        this.next = next;
    }

    public String toString() {
        String out = "";
        out += this.value;
        if (this.next != null) {
            out += " " + this.next.toString();
        }
        return out;
    }

    public static void main(String[] args) {
        LLNode first = new LLNode(1, null);
        first = new LLNode(2, first);
        first = new LLNode(3, first);
        String value = first.toString();
        System.out.println(value);
    }
}
```



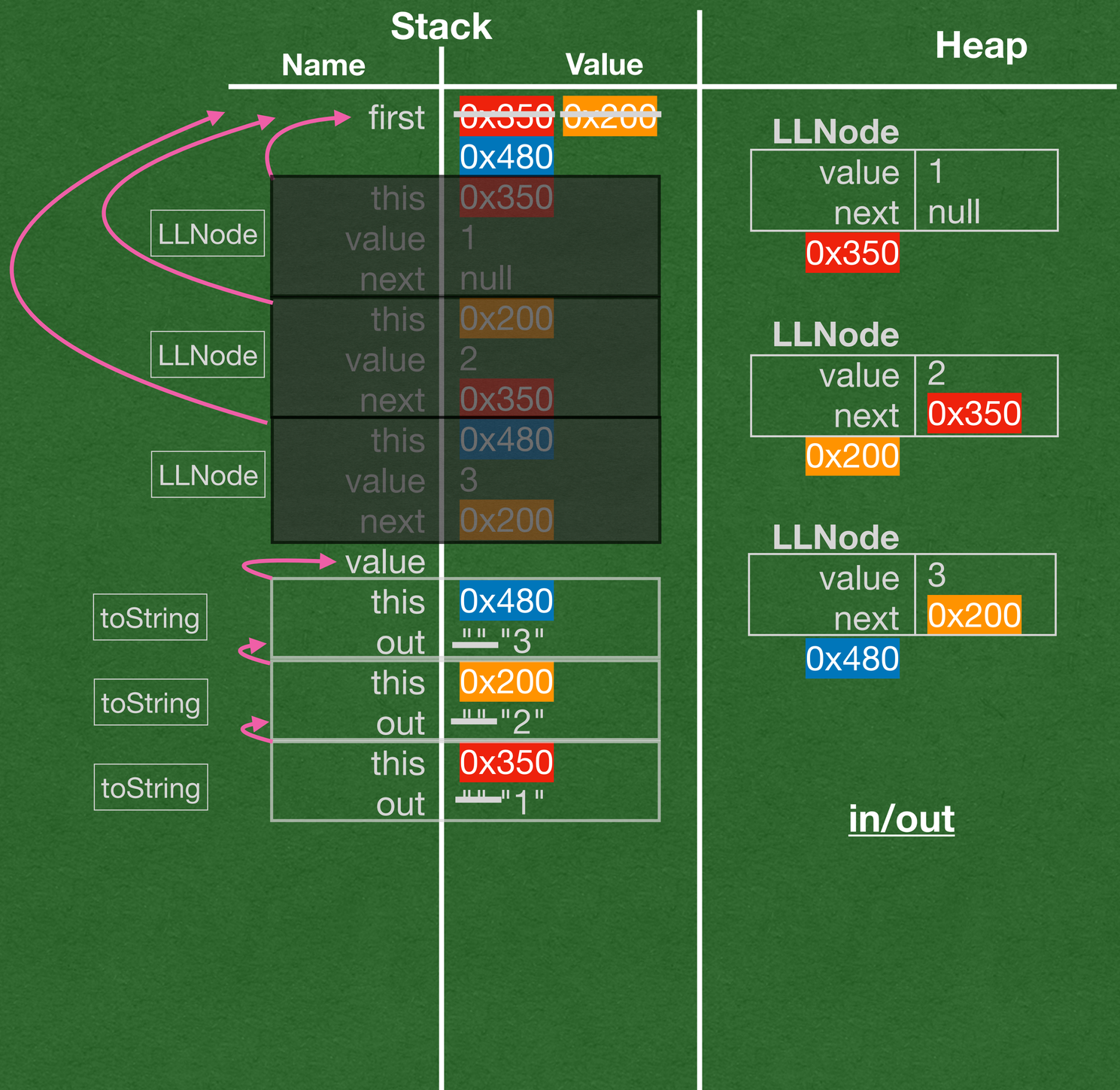
- Make another recursive call
- In this stack frame, the condition is false

```
public class LLNode {
    private int value;
    private LLNode next;

    public LLNode(int value, LLNode next) {
        this.value = value;
        this.next = next;
    }

    public String toString() {
        String out = "";
        out += this.value;
        if (this.next != null) {
            out += " " + this.next.toString();
        }
        return out;
    }

    public static void main(String[] args) {
        LLNode first = new LLNode(1, null);
        first = new LLNode(2, first);
        first = new LLNode(3, first);
        String value = first.toString();
        System.out.println(value);
    }
}
```



- This frame returns "1" to the previous stack frame

```
public class LLNode {
    private int value;
    private LLNode next;

    public LLNode(int value, LLNode next) {
        this.value = value;
        this.next = next;
    }

    public String toString() {
        String out = "";
        out += this.value;
        if (this.next != null) {
            out += " " + this.next.toString();
        }
        return out;
    }

    public static void main(String[] args) {
        LLNode first = new LLNode(1, null);
        first = new LLNode(2, first);
        first = new LLNode(3, first);
        String value = first.toString();
        System.out.println(value);
    }
}
```



- The previous stack frame (With this == 0x200) is back on top of the stack
- It takes the return value of "1" and continues running code

```
public class LLNode {
    private int value;
    private LLNode next;

    public LLNode(int value, LLNode next) {
        this.value = value;
        this.next = next;
    }

    public String toString() {
        String out = "";
        out += this.value;
        if (this.next != null) {
            out += " " + this.next.toString();
        }
        return out;
    }

    public static void main(String[] args) {
        LLNode first = new LLNode(1, null);
        first = new LLNode(2, first);
        first = new LLNode(3, first);
        String value = first.toString();
        System.out.println(value);
    }
}
```

- Return "2 1" to the first recursive stack frame

```
public class LLNode {
    private int value;
    private LLNode next;

    public LLNode(int value, LLNode next) {
        this.value = value;
        this.next = next;
    }

    public String toString() {
        String out = "";
        out += this.value;
        if (this.next != null) {
            out += " " + this.next.toString();
        }
        return out;
    }

    public static void main(String[] args) {
        LLNode first = new LLNode(1, null);
        first = new LLNode(2, first);
        first = new LLNode(3, first);
        String value = first.toString();
        System.out.println(value);
    }
}
```

- The frame with this == 0x480 is back on top of the stack
- Concatenate the returned value to out

```
public class LLNode {
    private int value;
    private LLNode next;

    public LLNode(int value, LLNode next) {
        this.value = value;
        this.next = next;
    }

    public String toString() {
        String out = "";
        out += this.value;
        if (this.next != null) {
            out += " " + this.next.toString();
        }
        return out;
    }

    public static void main(String[] args) {
        LLNode first = new LLNode(1, null);
        first = new LLNode(2, first);
        first = new LLNode(3, first);
        String value = first.toString();
        System.out.println(value);
    }
}
```

- Return "3 2 1" to the main method

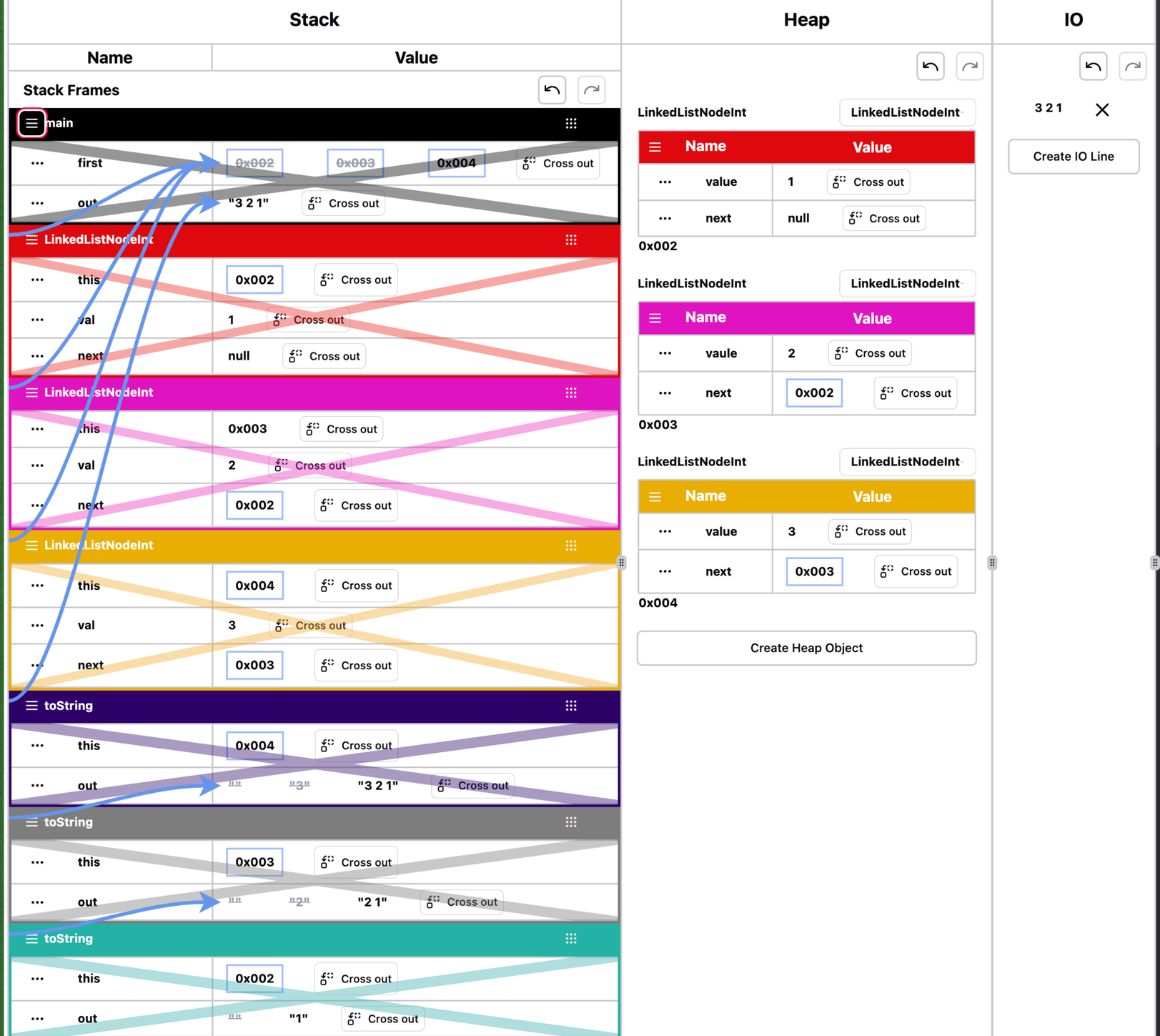
```
public class LLNode {
    private int value;
    private LLNode next;

    public LLNode(int value, LLNode next) {
        this.value = value;
        this.next = next;
    }

    public String toString() {
        String out = "";
        out += this.value;
        if (this.next != null) {
            out += " " + this.next.toString();
        }
        return out;
    }

    public static void main(String[] args) {
        LLNode first = new LLNode(1, null);
        first = new LLNode(2, first);
        first = new LLNode(3, first);
        String value = first.toString();
        System.out.println(value);
    }
}
```

- Assign "3 2 1" to value in the main stack frame
- We only called toString on the head of the list, but got all the values of the list

```
public class LLNode {
    private int value;
    private LLNode next;

    public LLNode(int value, LLNode next) {
        this.value = value;
        this.next = next;
    }

    public String toString() {
        String out = "";
        out += this.value;
        if (this.next != null) {
            out += " " + this.next.toString();
        }
        return out;
    }

    public static void main(String[] args) {
        LLNode first = new LLNode(1, null);
        first = new LLNode(2, first);
        first = new LLNode(3, first);
        String value = first.toString();
        System.out.println(value);
    }
}
```

- Print to the screen and program ends

```
public class LLNode {
    private int value;
    private LLNode next;

    public LLNode(int value, LLNode next) {
        this.value = value;
        this.next = next;
    }

    public String toString() {
        String out = "";
        out += this.value;
        if (this.next != null) {
            out += " " + this.next.toString();
        }
        return out;
    }

    public static void main(String[] args) {
        LLNode first = new LLNode(1, null);
        first = new LLNode(2, first);
        first = new LLNode(3, first);
        String value = first.toString();
        System.out.println(value);
    }
}
```




```java
package week5;

public class LinkedListNodeInt {
    private int value;
    private LinkedListNodeInt next;

    public LinkedListNodeInt(int val, LinkedListNodeInt next) {
        this.value = val;
        this.next = next;
    }

    public String toString() {
        String out = "";
        out += this.value;
        if (this.next != null) {
            out += " " + this.next.toString();
        }
        return out;
    }

    public static void main(String[] args) {
        LinkedListNodeInt first = new LinkedListNodeInt(1, null);
        first = new LinkedListNode<>(2, first);
        first = new LinkedListNode<>(3, first);
        String out = first.toString();
        System.out.println(out);
    }
}

```