# Algorithms, C, Systems

**Lecture 4: Memory, malloc, structs, etc.**

**CS 5006**
**Spring 2019**
**Seattle**

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# ASK ME IF I'm RECORDING!!

# Agenda

- Review from last time/summarize
- More structs
- Malloc & Free
- Review:
  - Abstract Data Types
  - Queues
  - Compare/contrast Linked Lists, Stacks, Queues

# MORE MALLOC & FREE

# Pattern 1: Declare variable, function to initialize

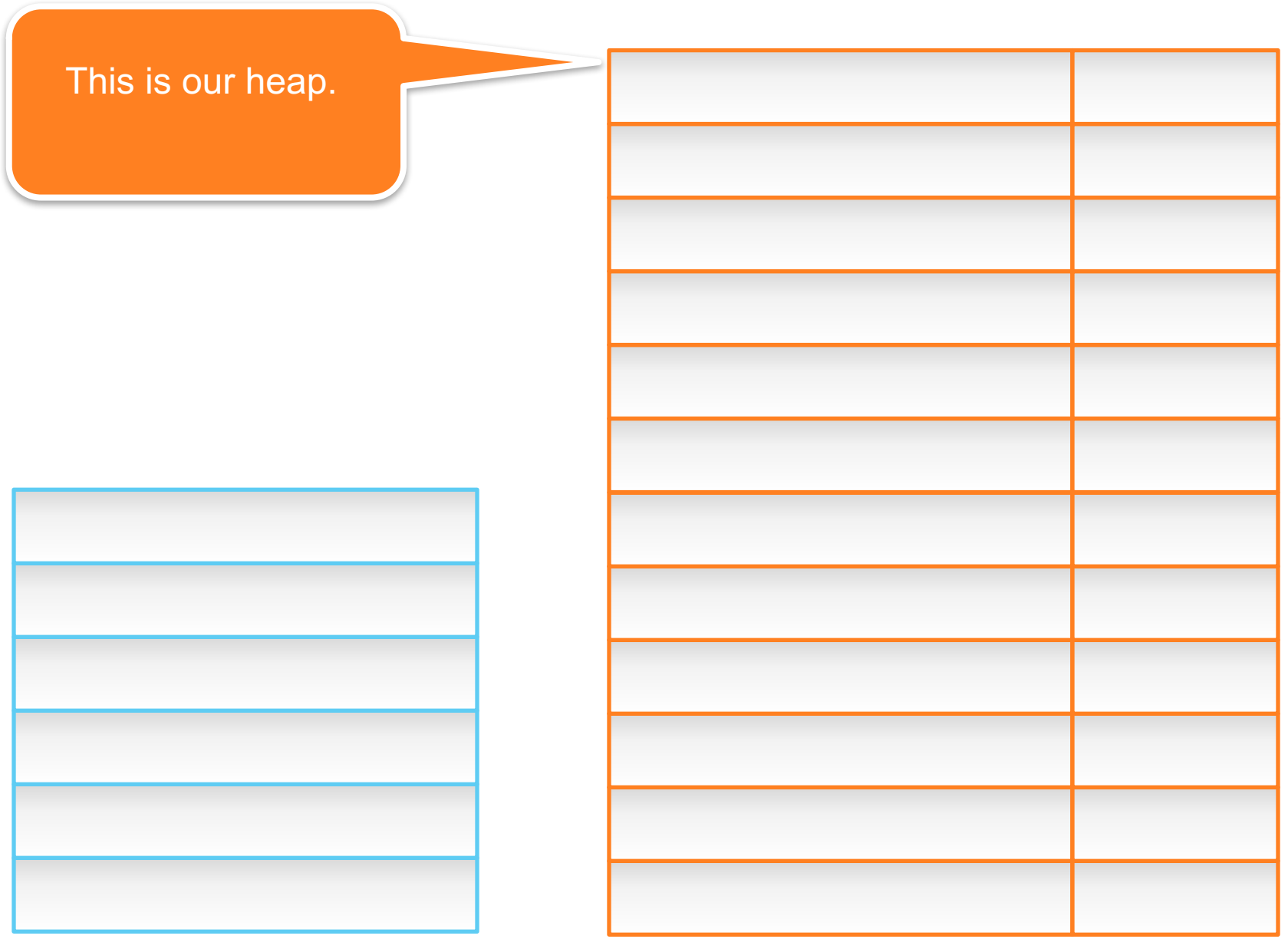
- Pros? Cons?

# Pattern 2:

- Write a function to declare and initialize a variable,
- Return a pointer to it
- Free the pointer later

# Memory: Storing Variables

- **Global:** available to the whole program
- **Local (stack):** available "in scope"– in a function
- **Heap:** available to the program


This is our heap.
Stack
(Memory, not the data structure)
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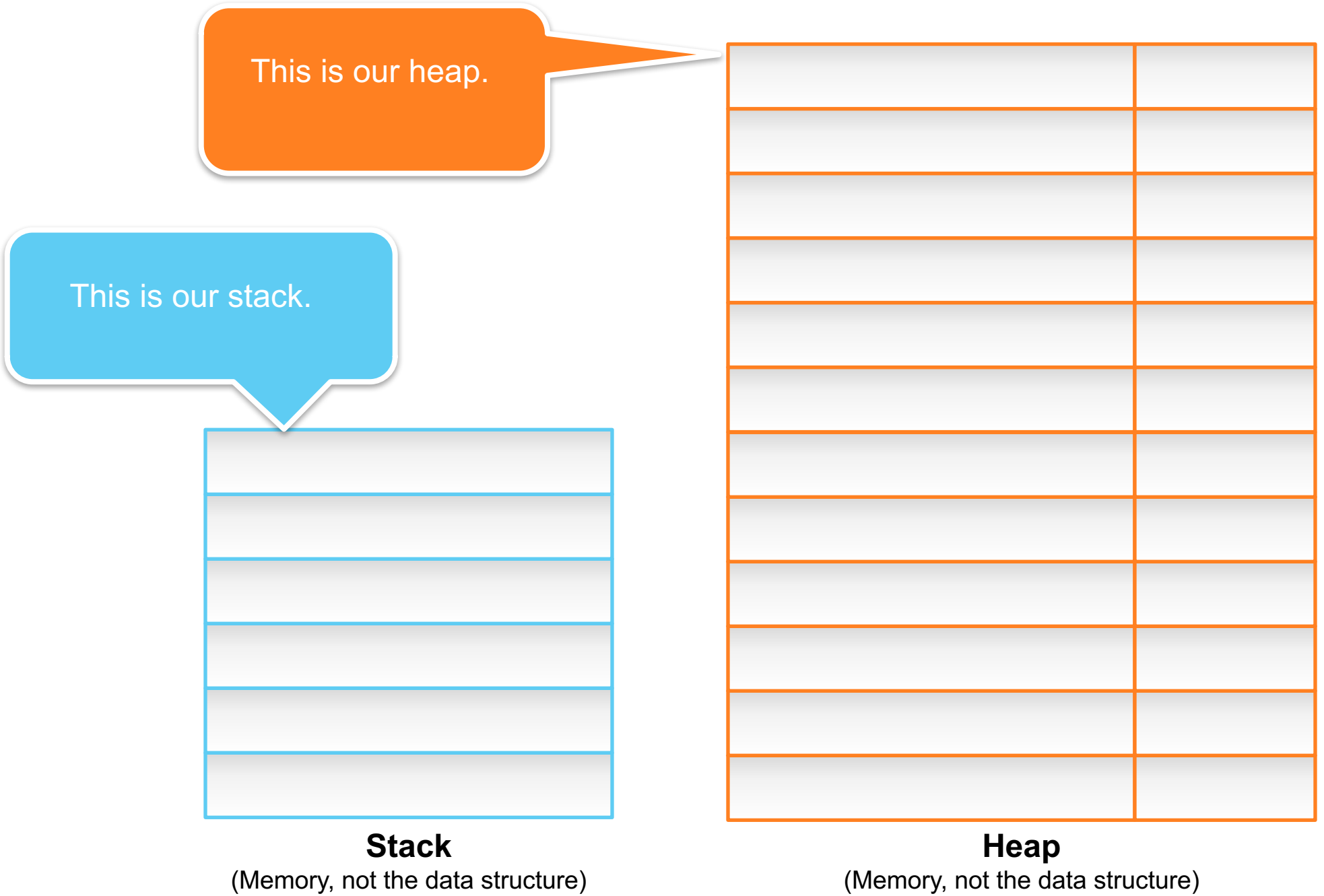
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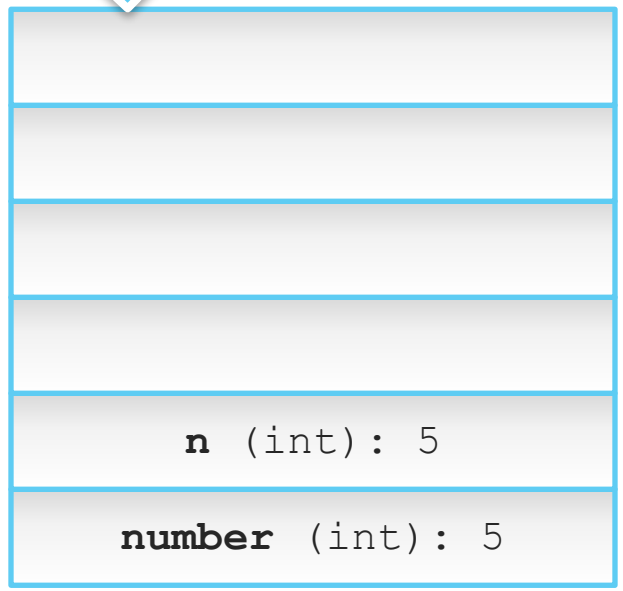
```
10  int number = 5;
11
12  printf("The original value of the number is %d\n", number);
13  number = cubeByValue(number);
```

This is our stack.

```
19int cubeByValue(int n) {
20   return n*n*n;
21}
```




**Stack**

(Memory, not the data structure)

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19}
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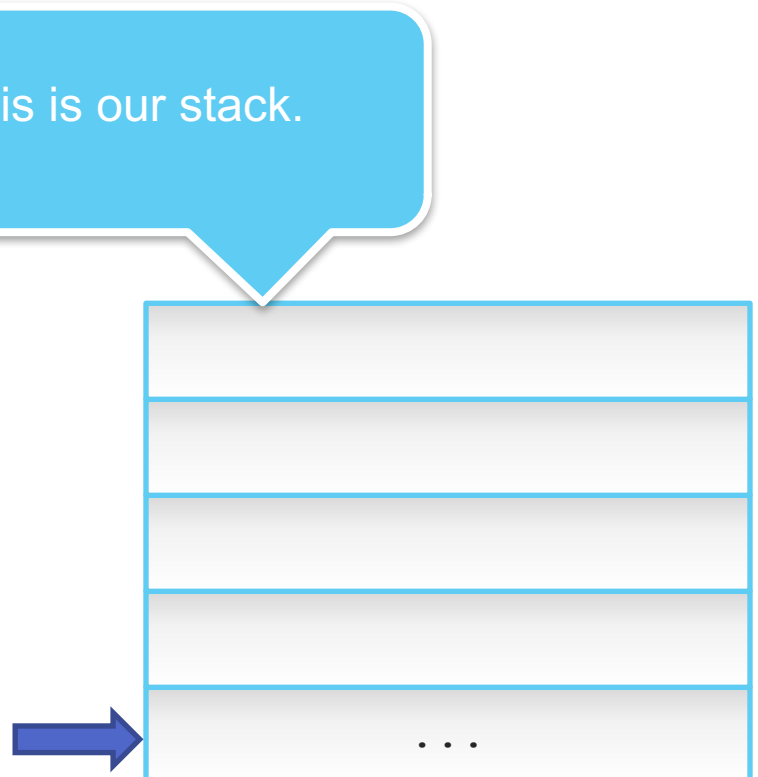


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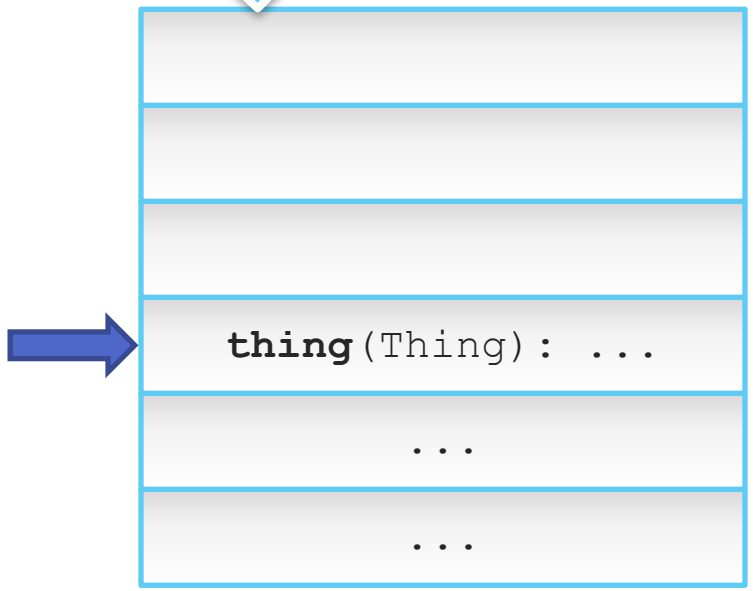


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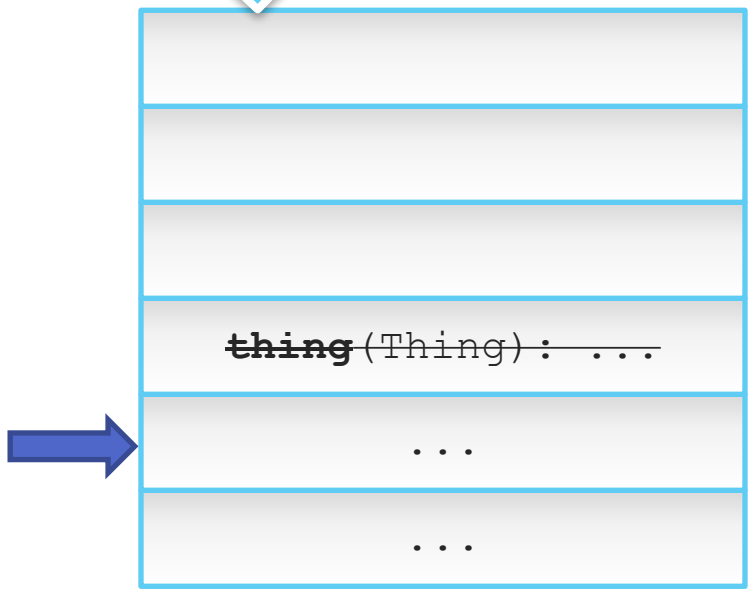


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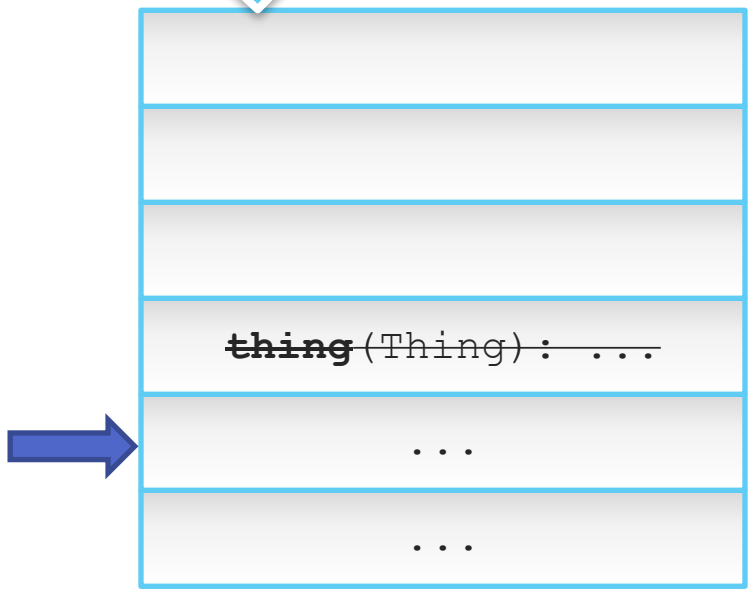


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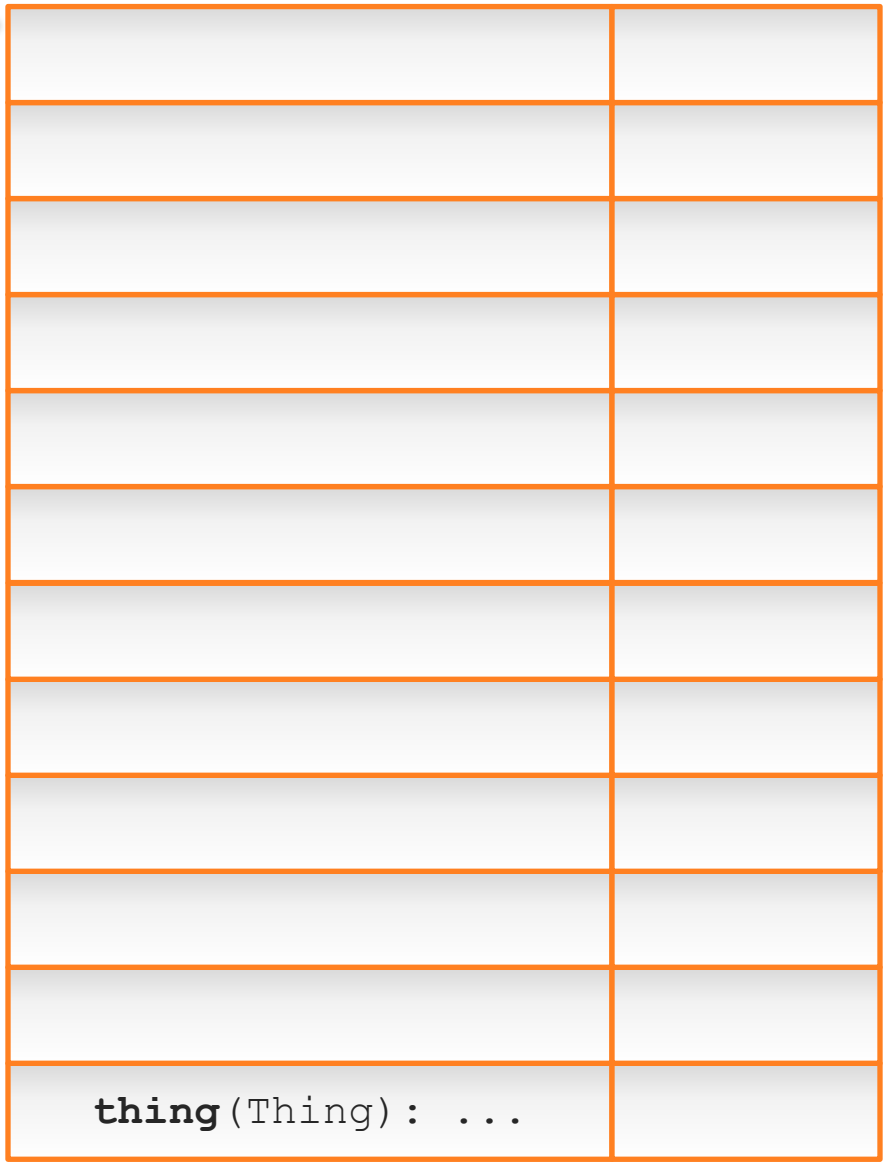


**Heap**
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# Malloc:

- Allocates memory "on the heap".
- Returns a value of type void*
- Cast it into the pointer type you care about
- Don't forget to free() the pointer when you're done with it

# A little deeper on malloc & free

- These slides illustrate what happens on the stack and the heap when running some code

# For reference, here's the code we start with:

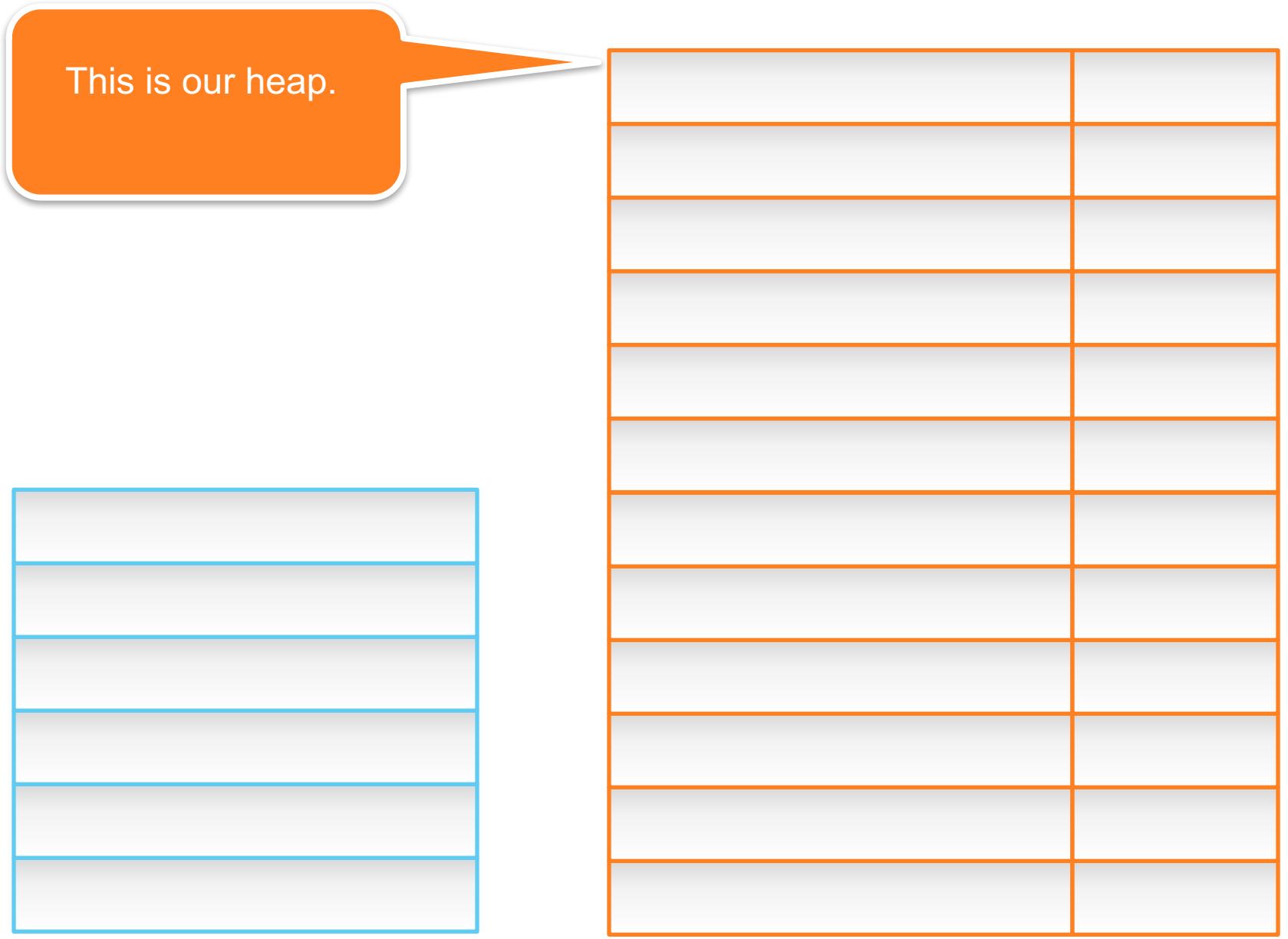
```
int main(){printf("first ");
        List *list = create();

        Node *head = createNode();
        head->data = "First Node";
        insert(list, head);

        Node *newNode = createNode();
        newNode -> data = "Second Node";
        insert(list, newNode);
        Node *node3 = createNode();
        node3->data = "Third Node";
        insert(list, node3);
        printf("printing the linked list, with 3 nodes recently created: \n");
        printLinkedList(list);
        printf("\n-------\n");
}
```

```
struct Node{
    char* data;
    Node* prevNode;
    Node* nextNode;
};
```

```
struct LinkedList{
    Node* firstNode;
};
```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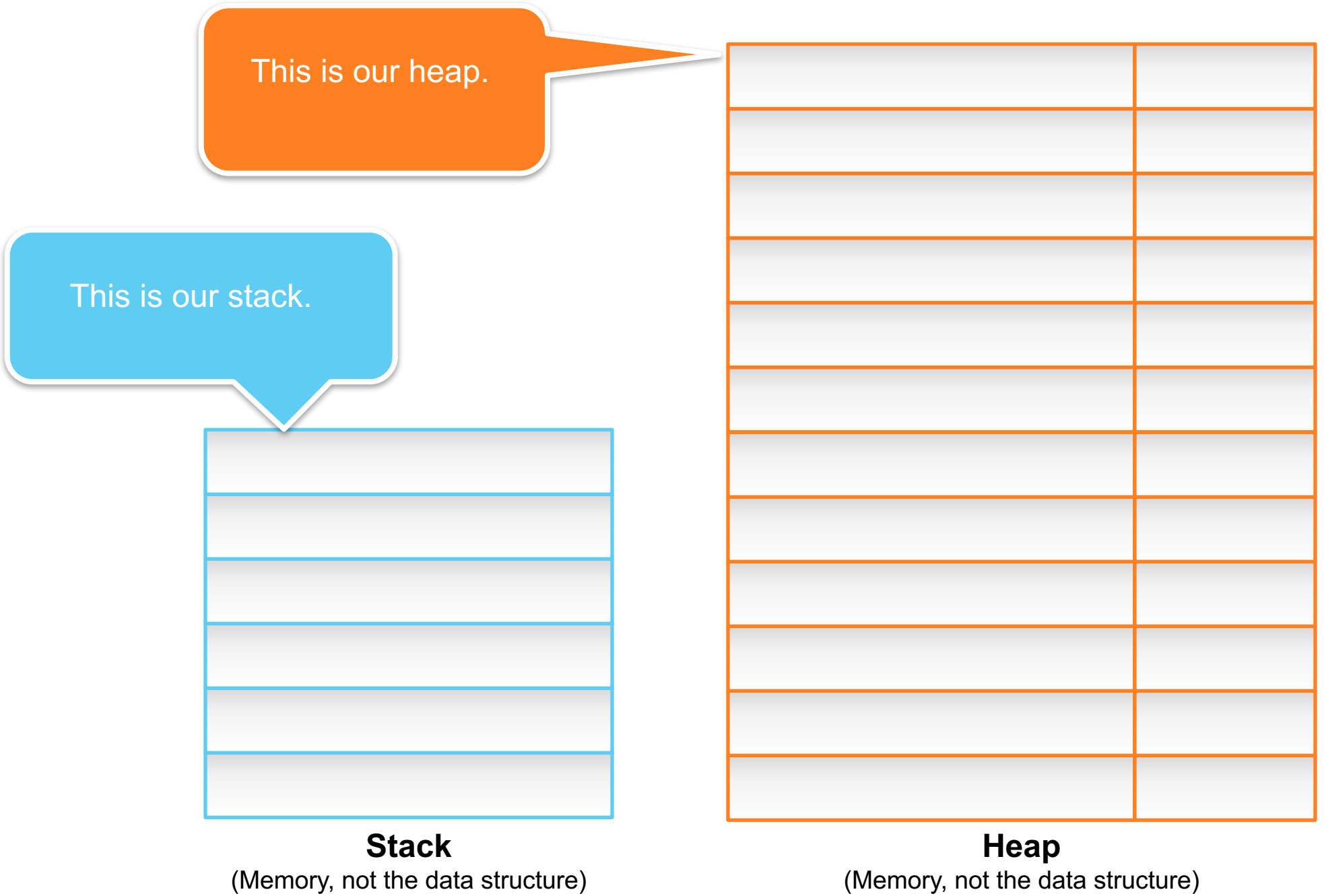
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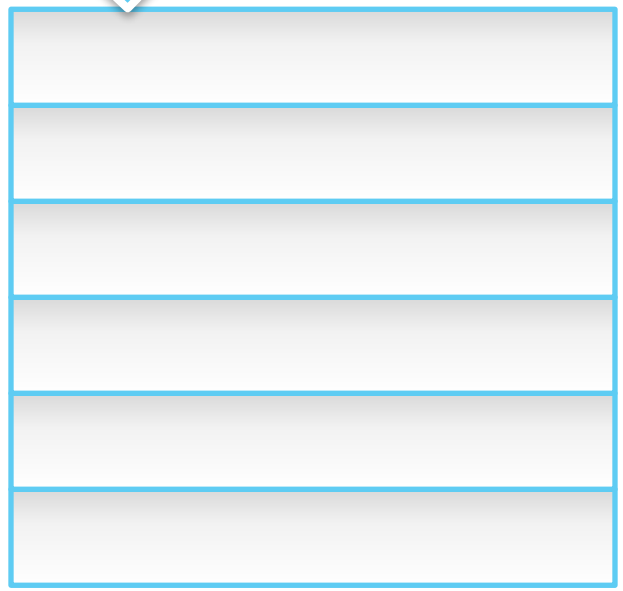

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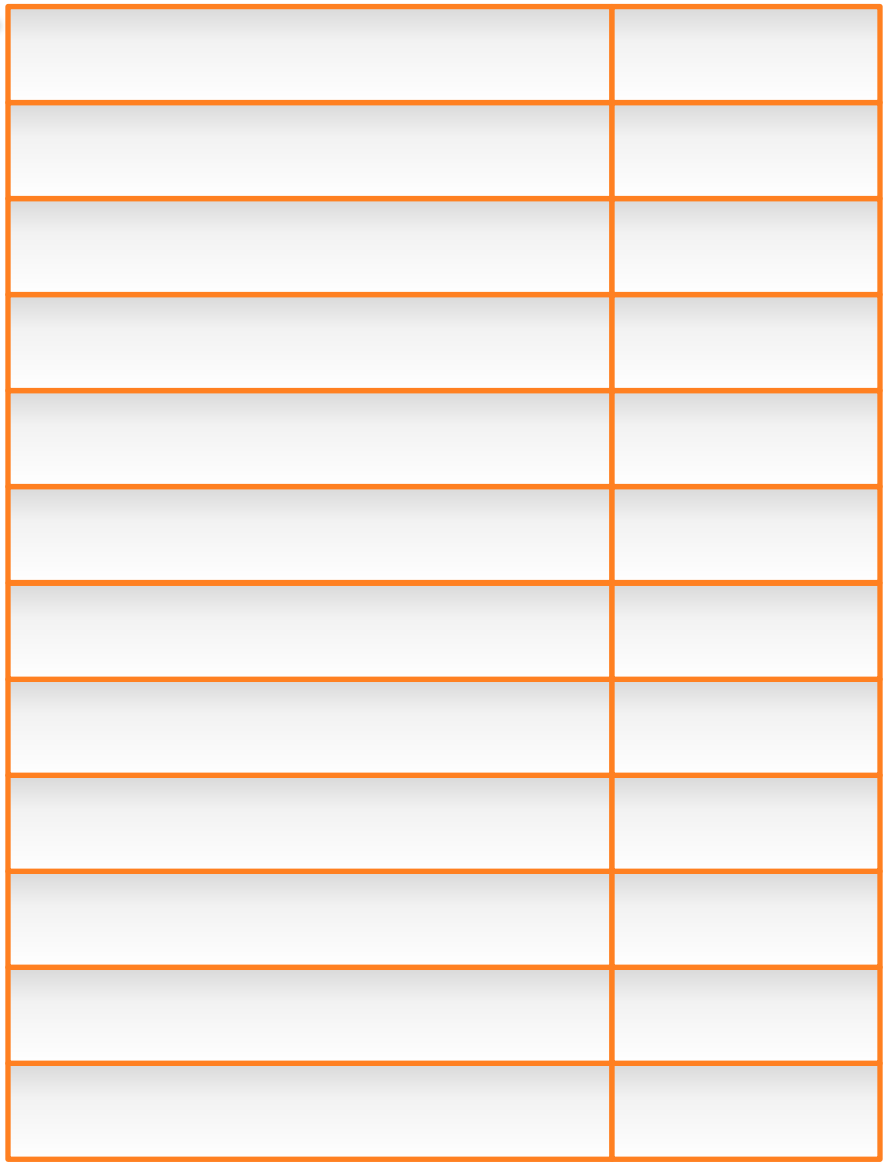

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When we run some code, the line is highlighted here… …and the memory changes are highlighted here.


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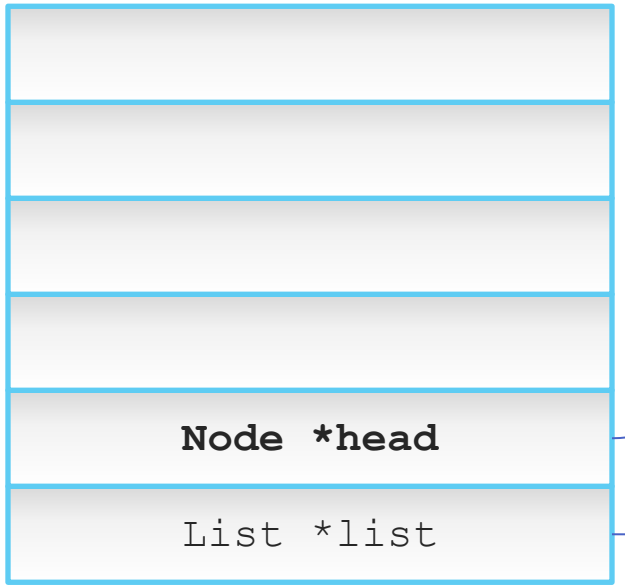


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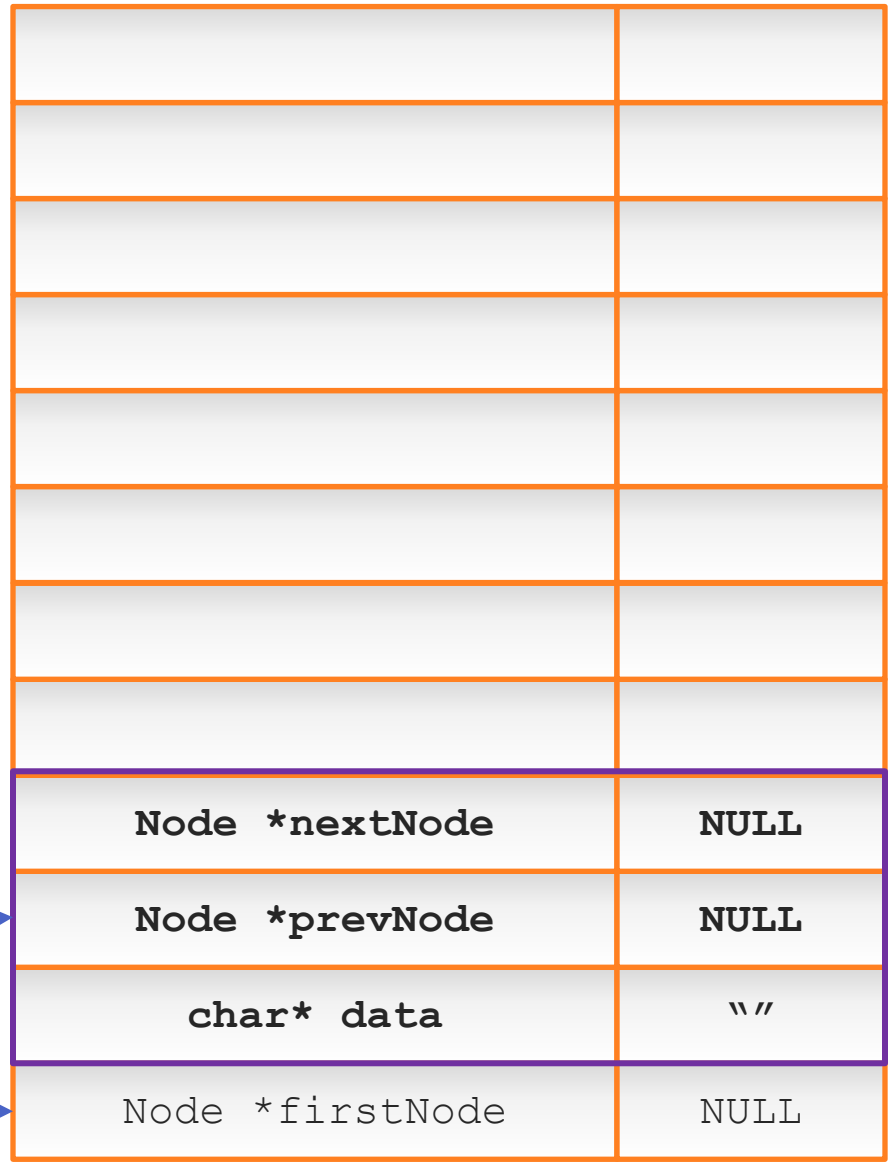


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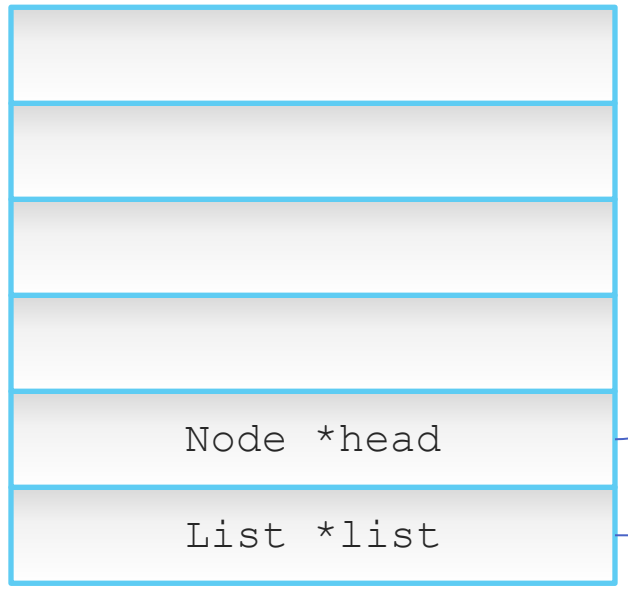


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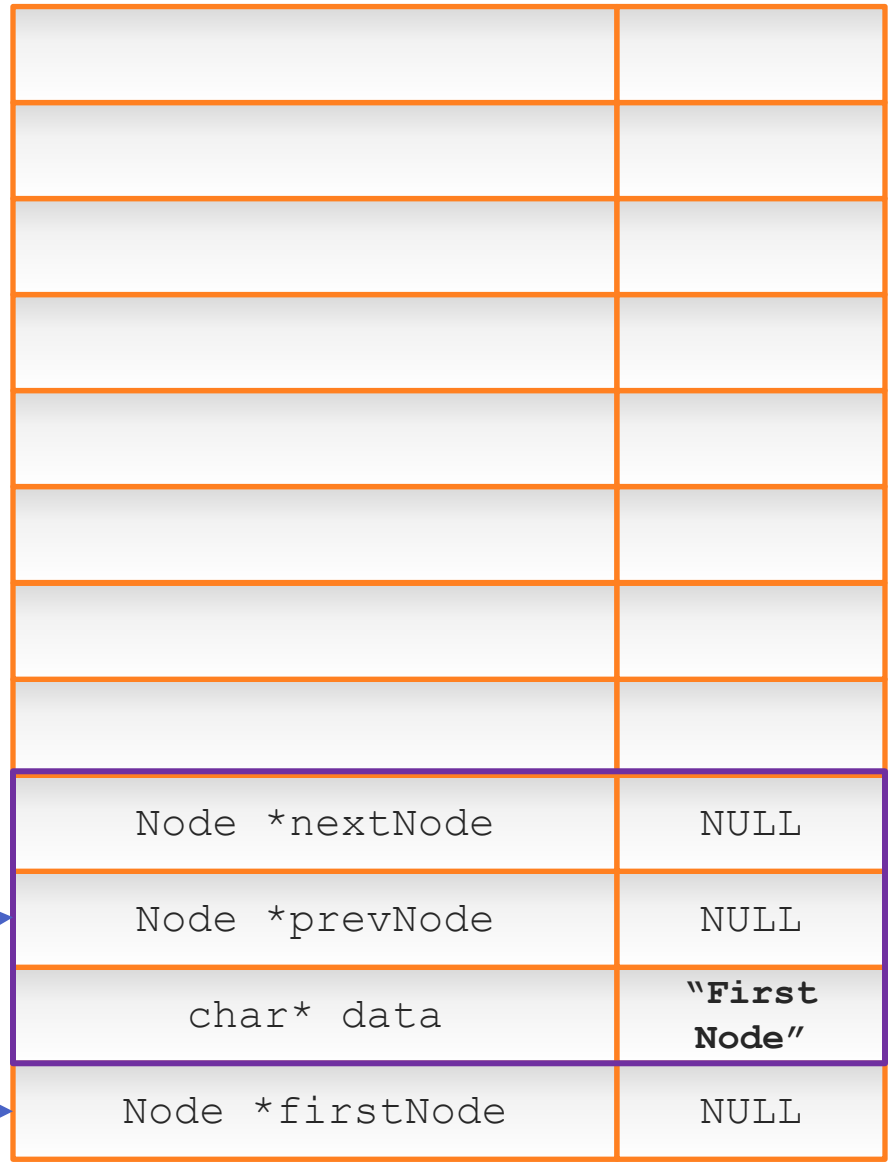


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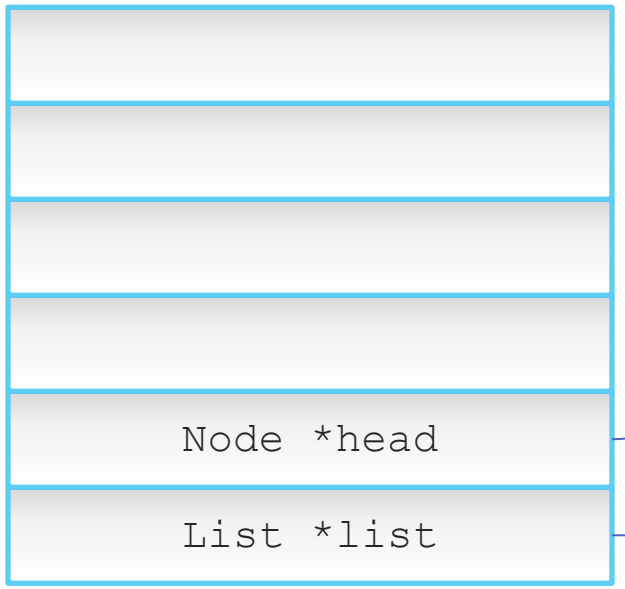


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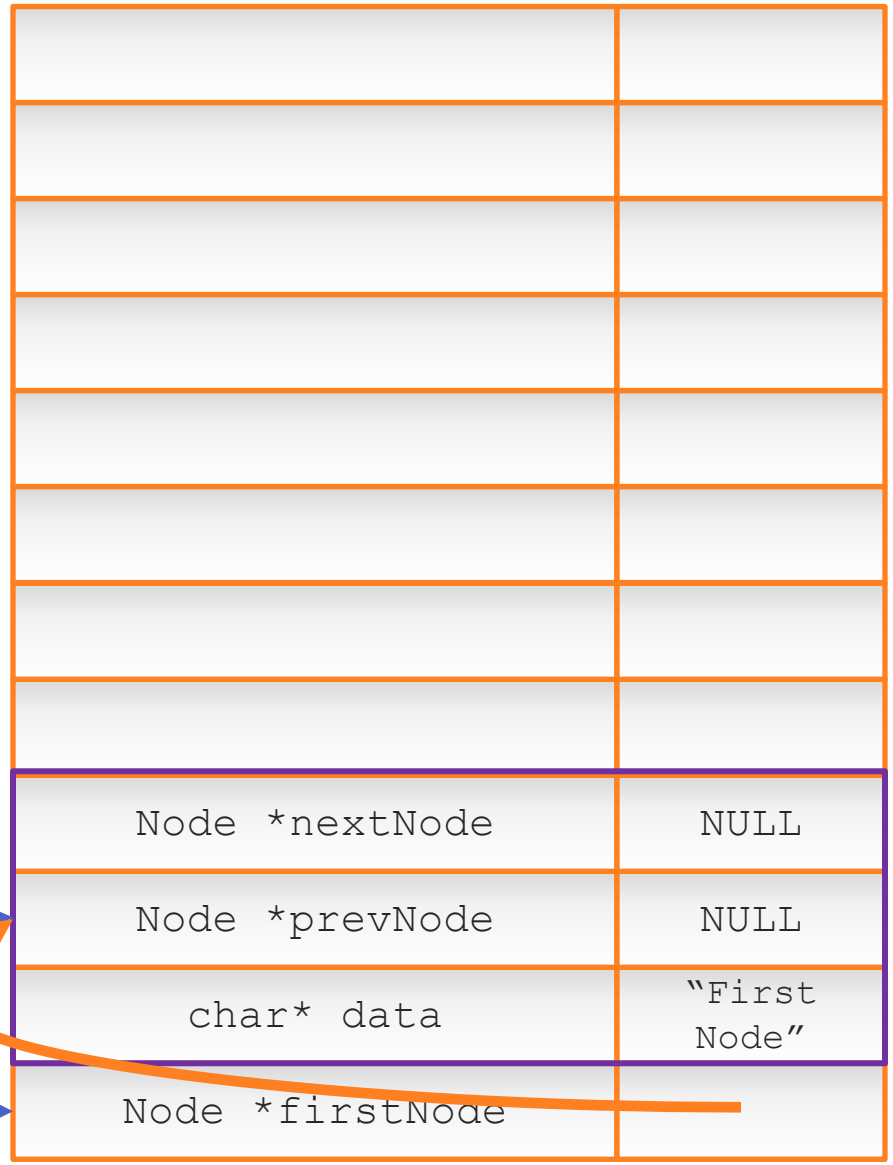


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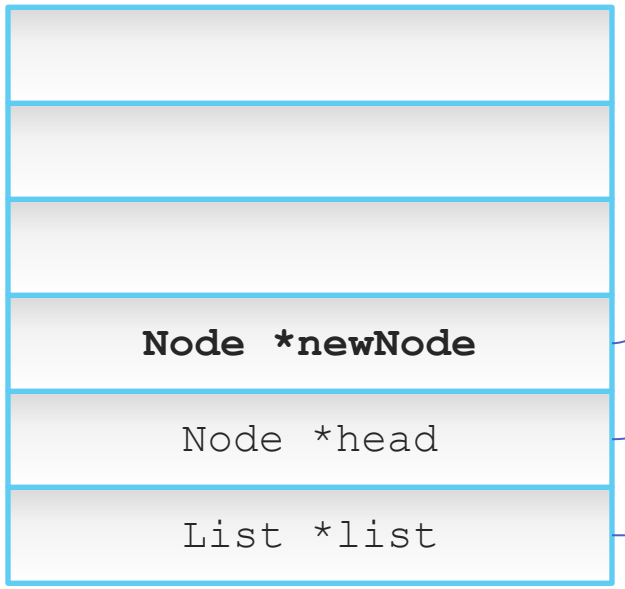


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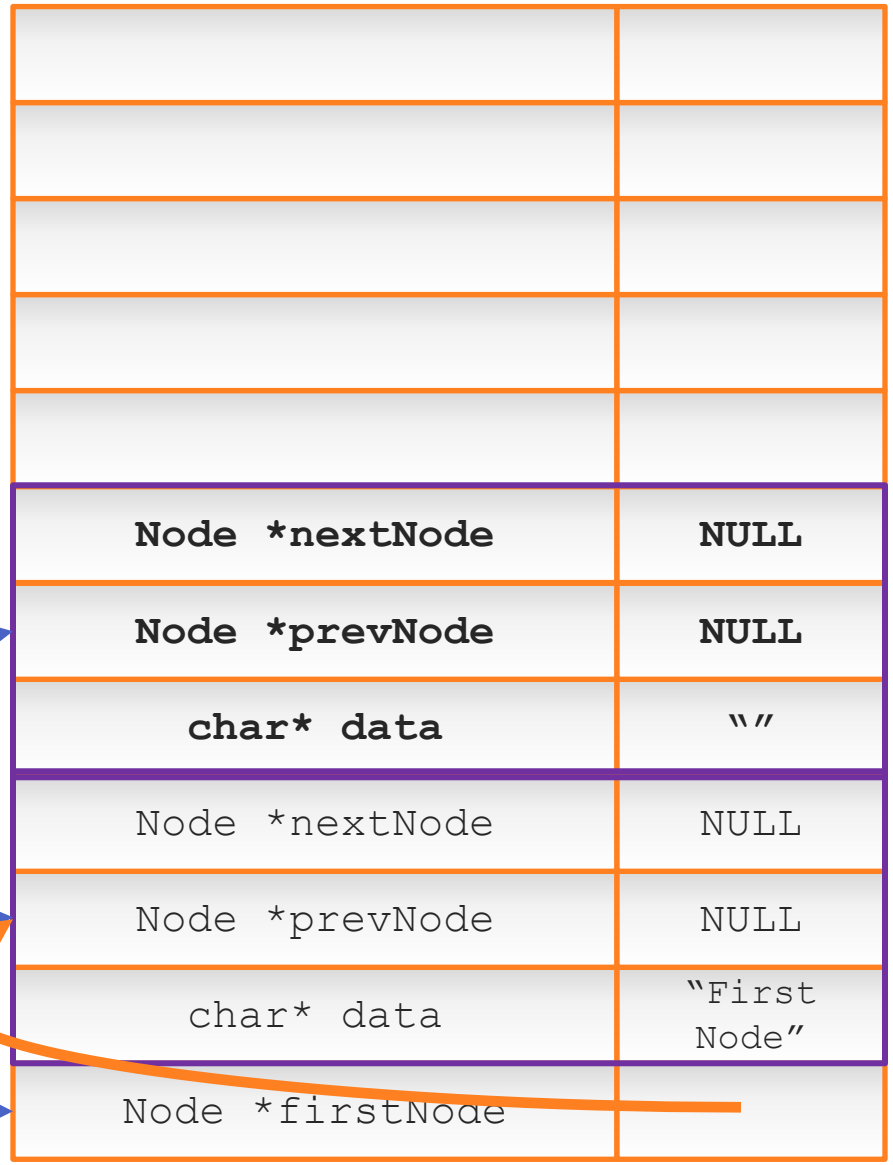


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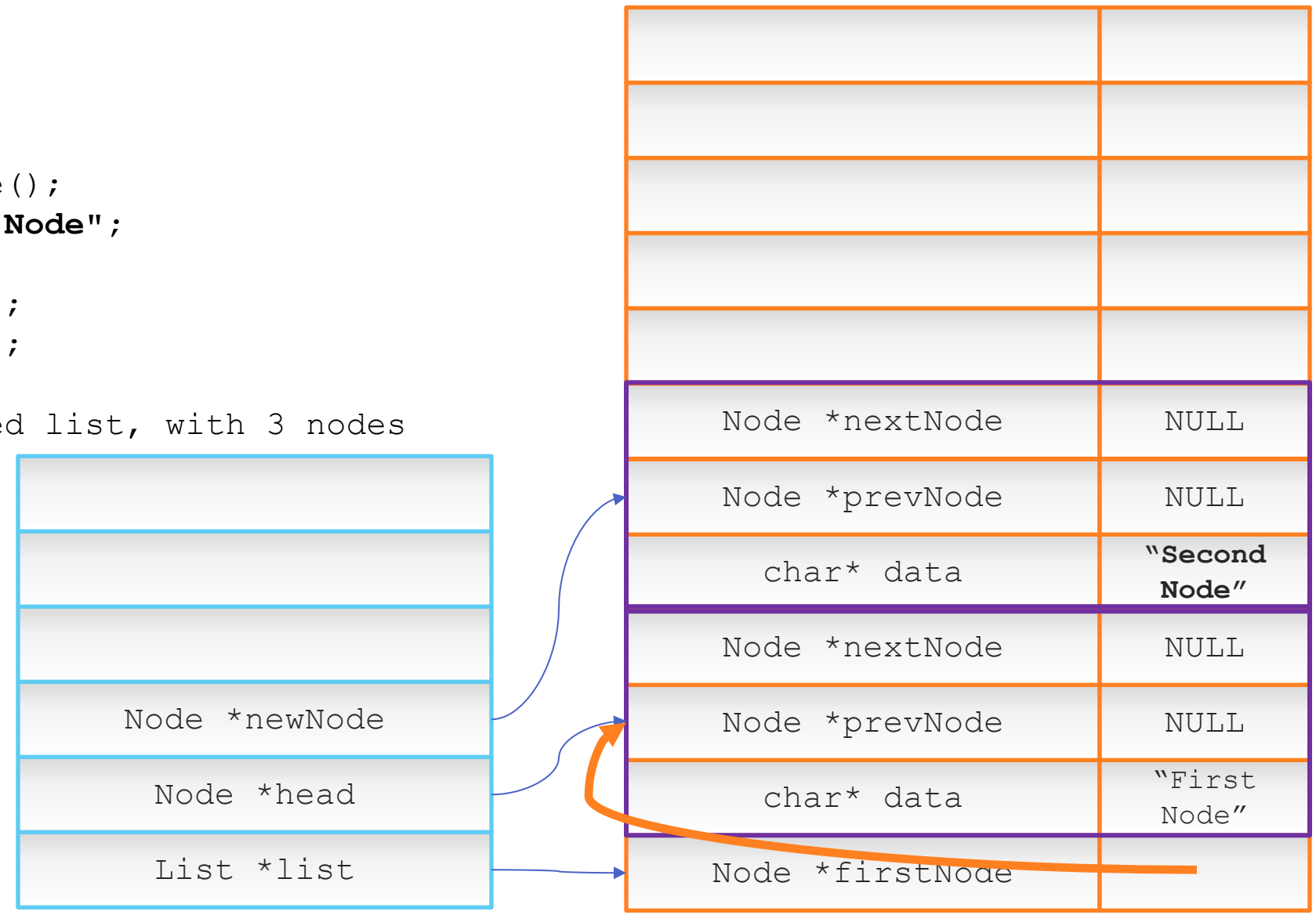


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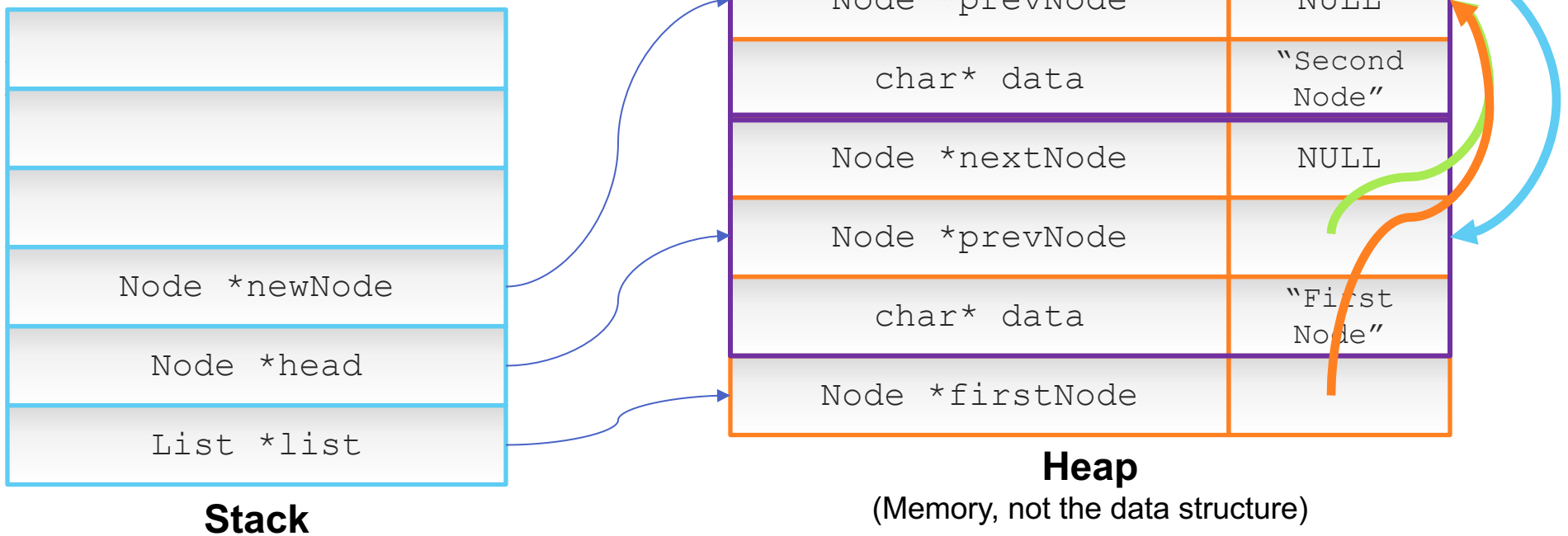

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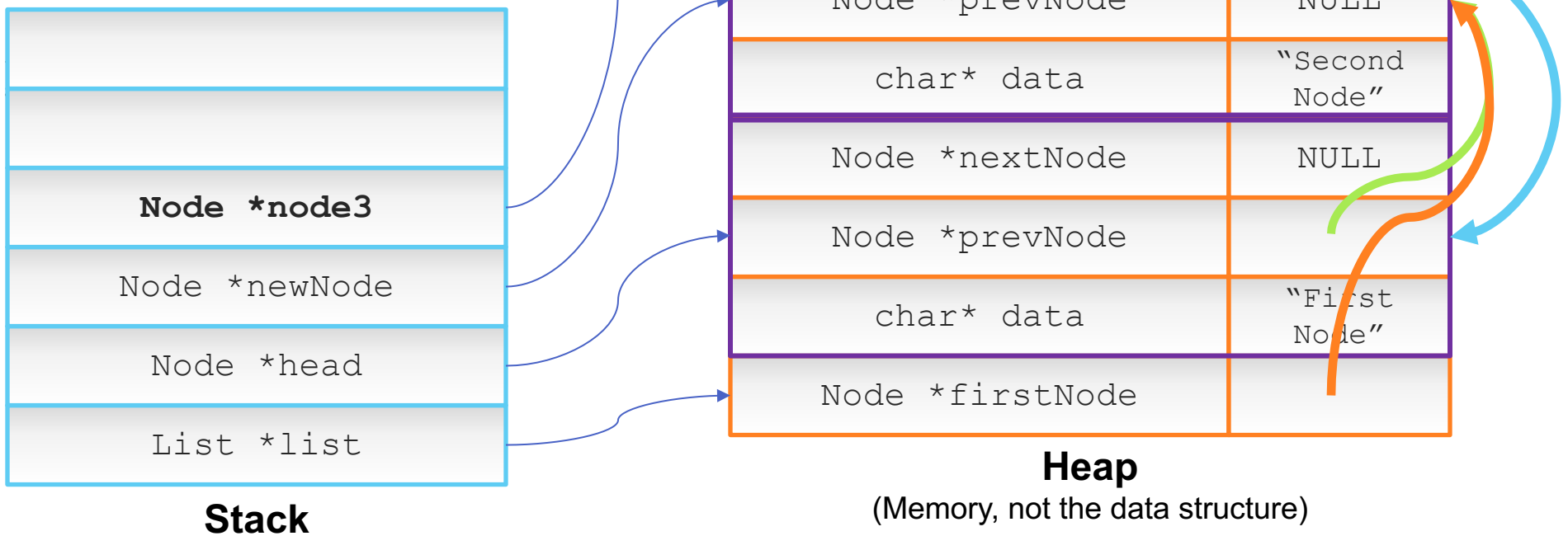

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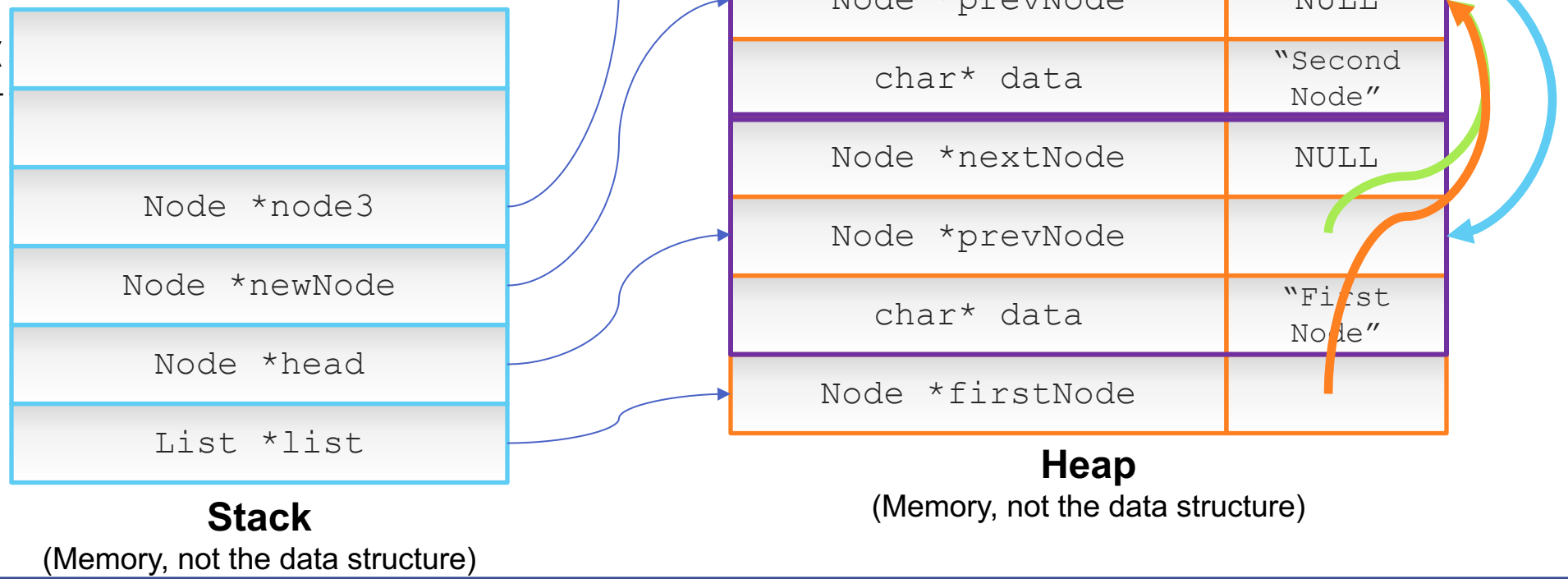

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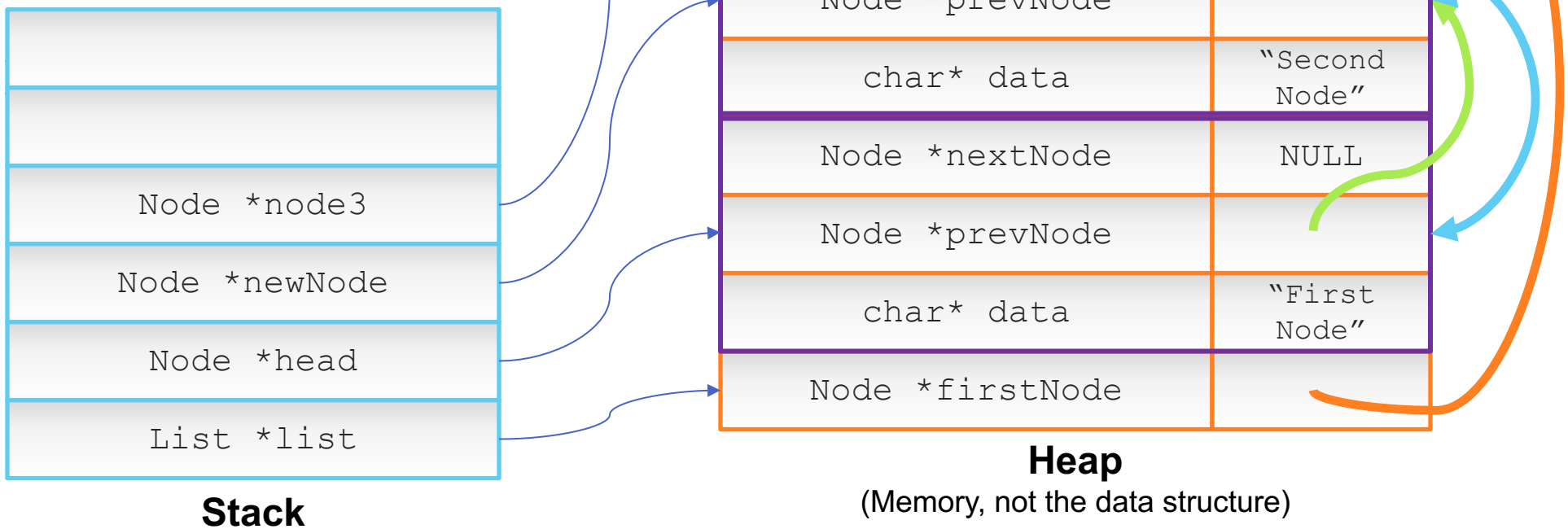

```
int main(){printf("first ");
```

```
printing the linked list, with 3 nodes recently created:
0x7ff16cc02720  PrevNode:                0x0|          Third Node| NextNode:  0x7ff16cc02700
0x7ff16cc02700  PrevNode:  0x7ff16cc02720|         Second Node| NextNode:  0x7ff16cc026e0
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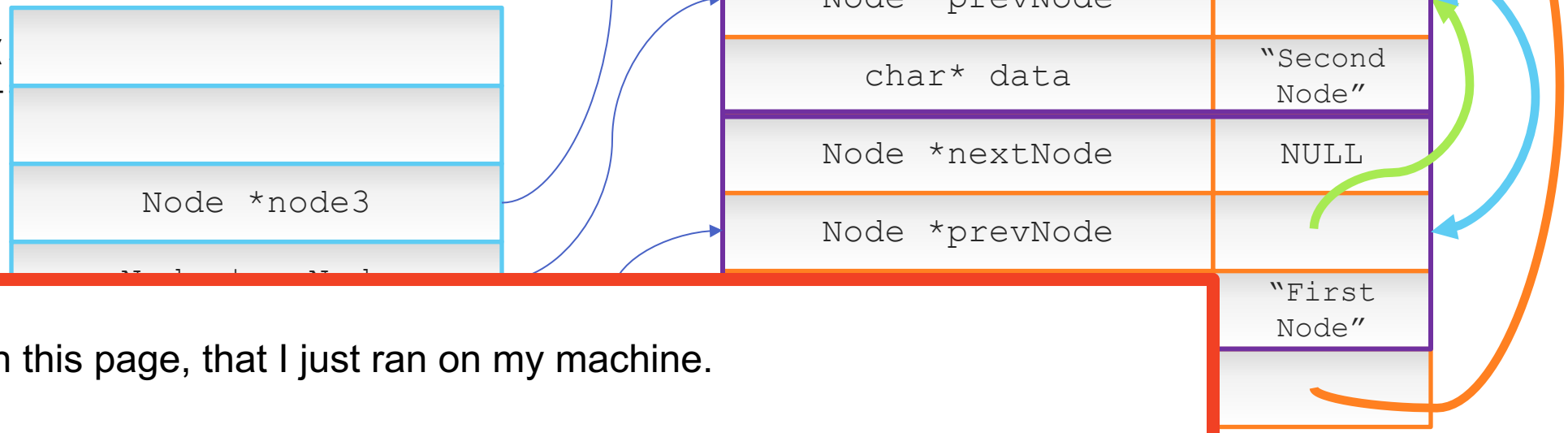



This is the output of the on this page, that I just ran on my machine.

Note that this is what we should expect: Printing our list, with 3 nodes.

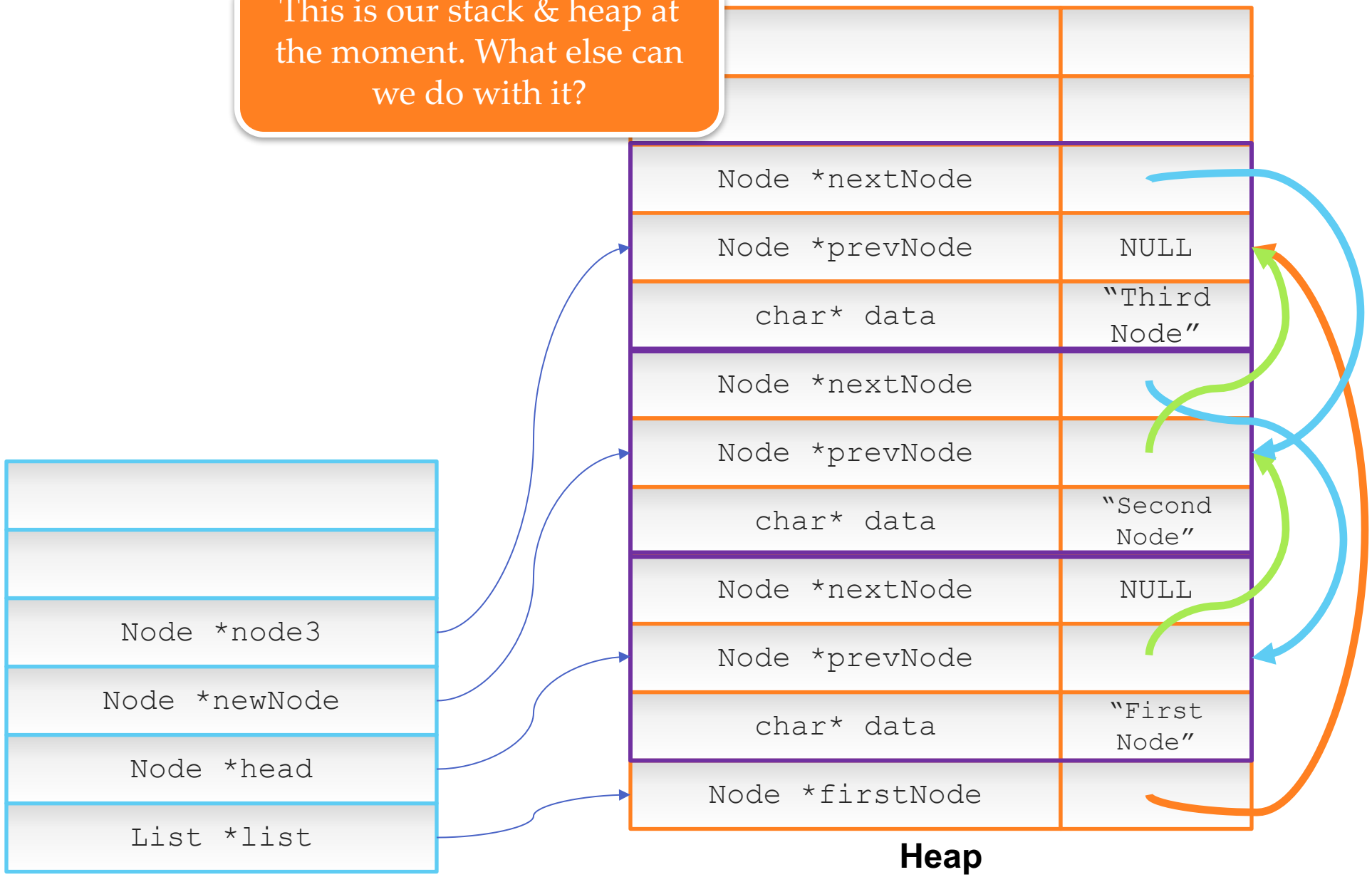
cture)

(Memory, not the data structure)

```
    …
    // Continuing on…

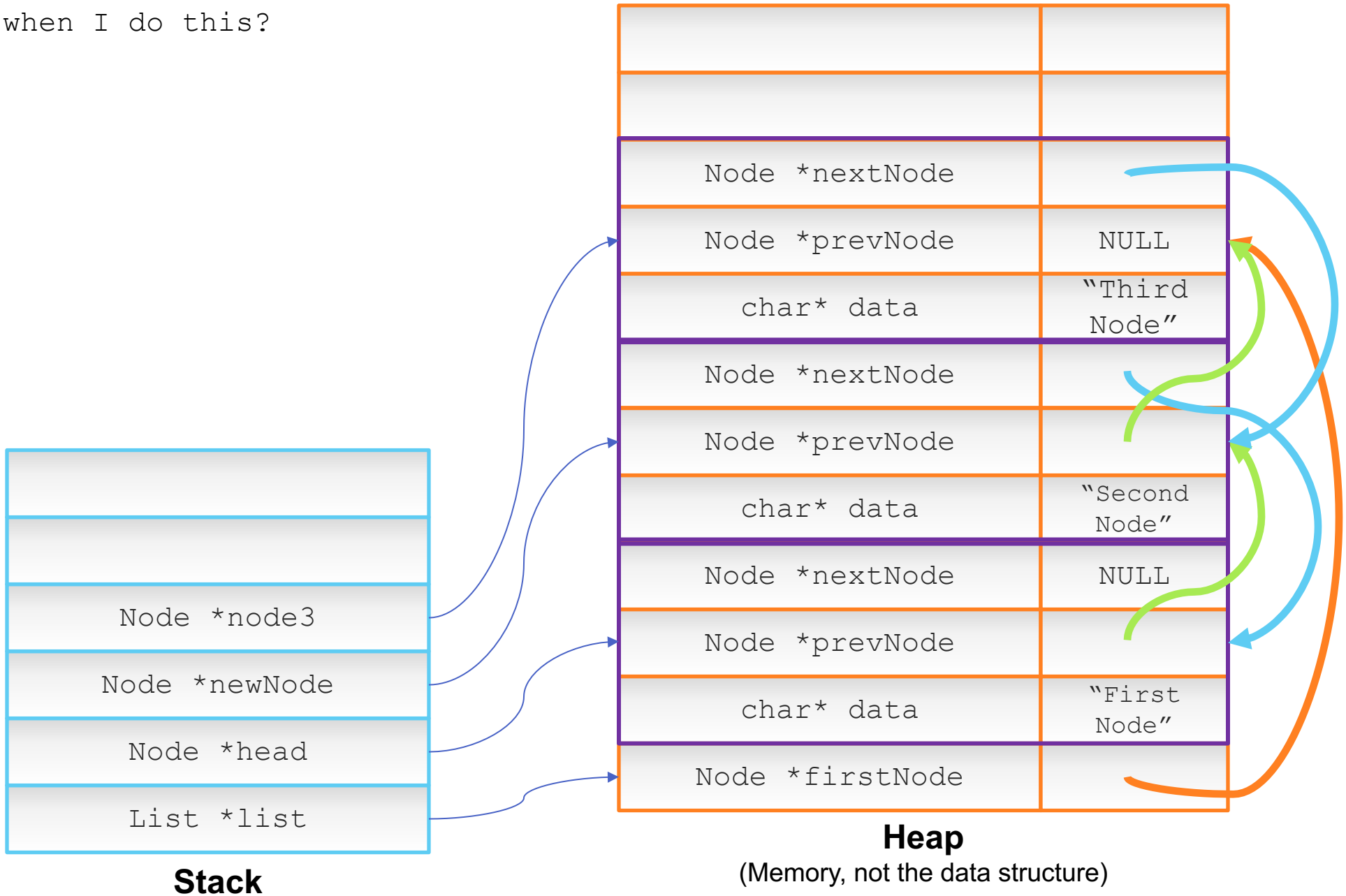

}
```

This is our stack & heap at the moment. What else can we do with it?



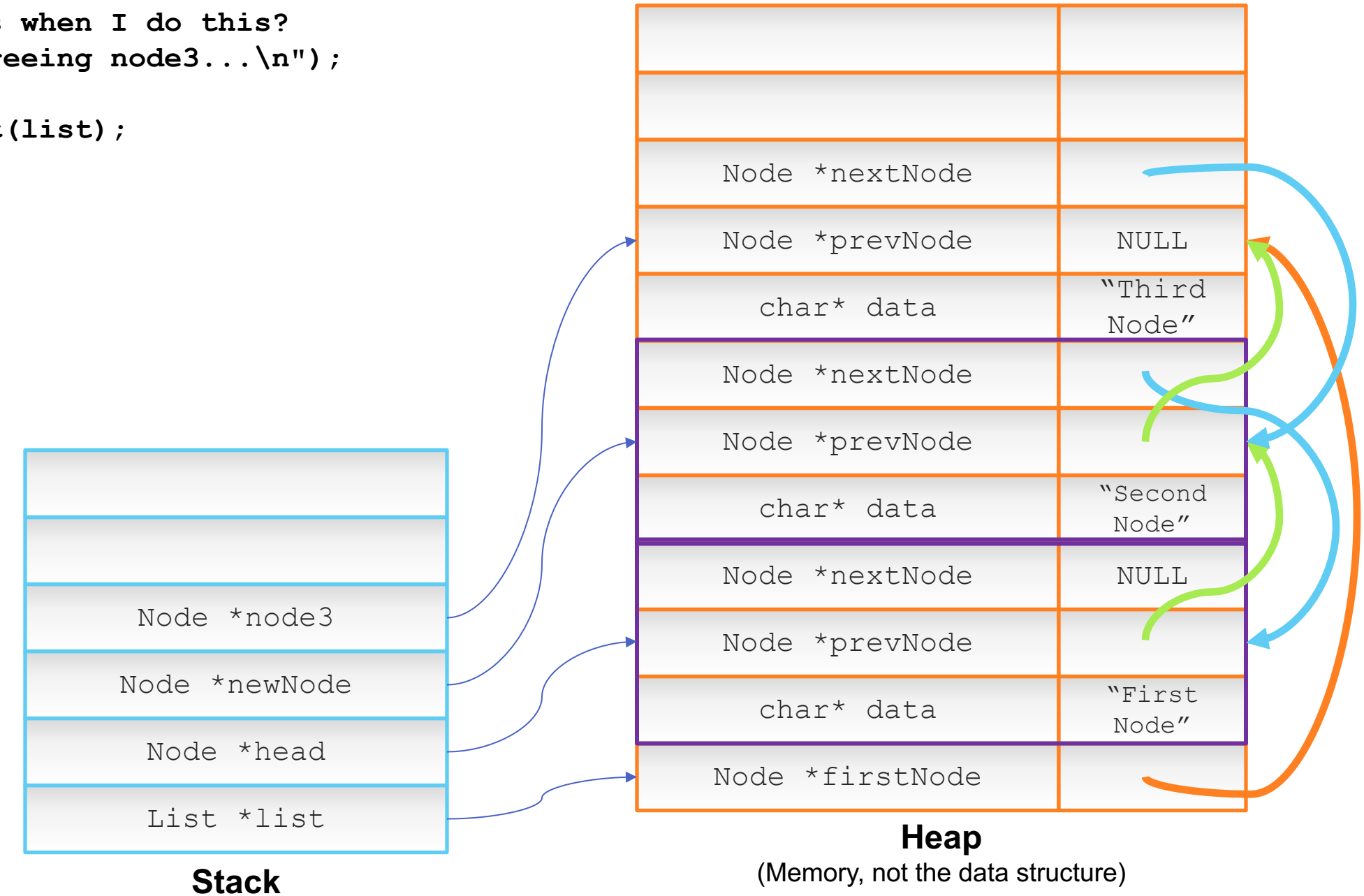
```
    …
    // Continuing on…
    // What happens when I do this?
    free(node3);


}
```



```
…
// Continuing on…
// What happens when I do this?
 printf("I'm freeing node3...\n");
free(node3);
printLinkedList(list);

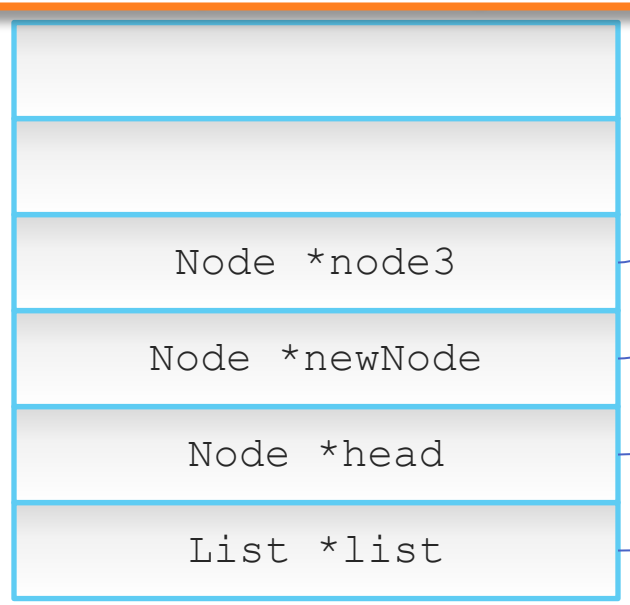
}
```



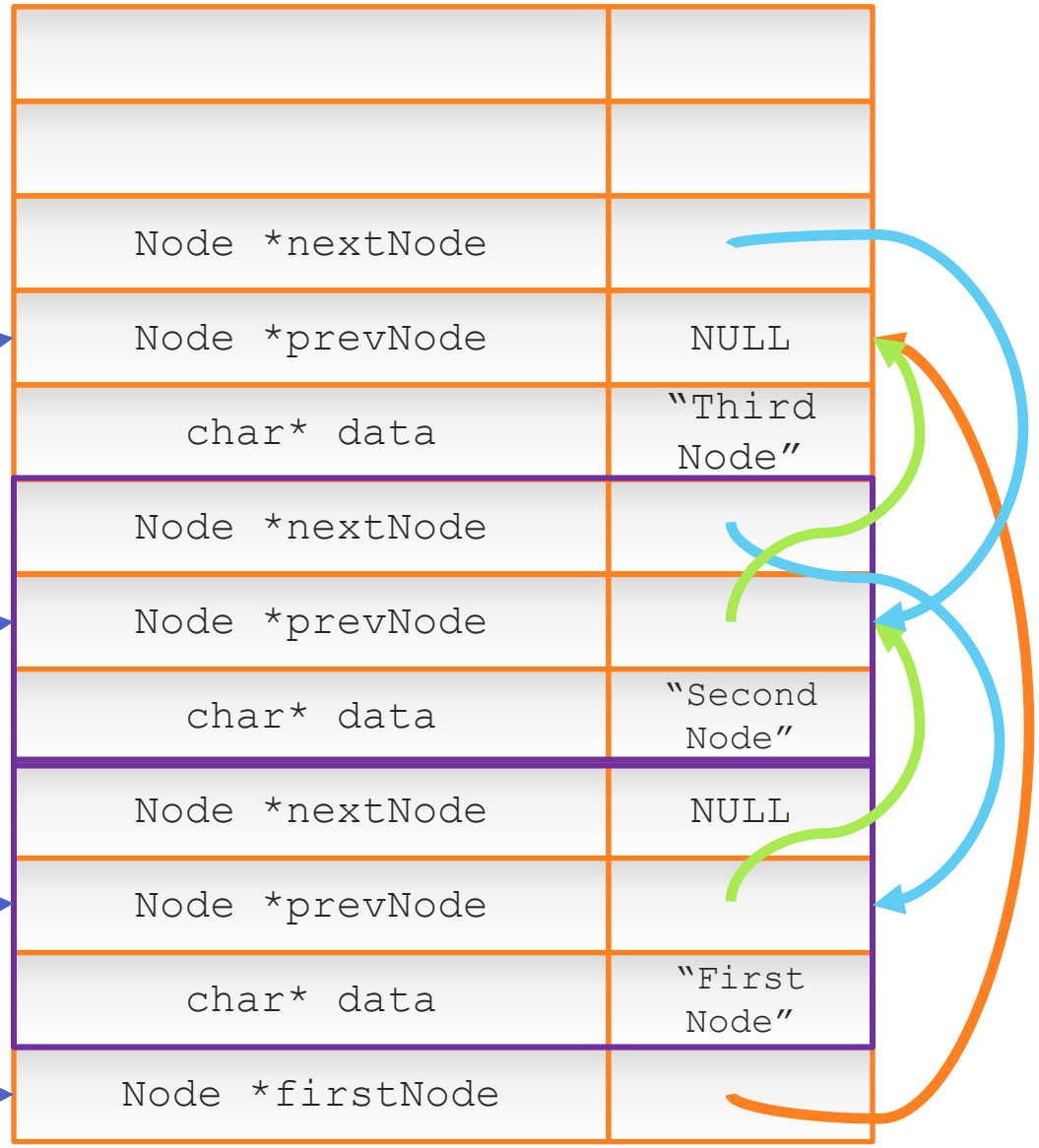
```
…
// Continuing on…
// What happens when I do this?
 printf("I'm freeing node3...\n");
free(node3);
printLinkedList(list);

}
```

→ The blue square goes away.
→ This means that the heap has deallocated the memory, or released it.
→ **NOTE:** Nothing else has changed. There are still pointers everywhere!



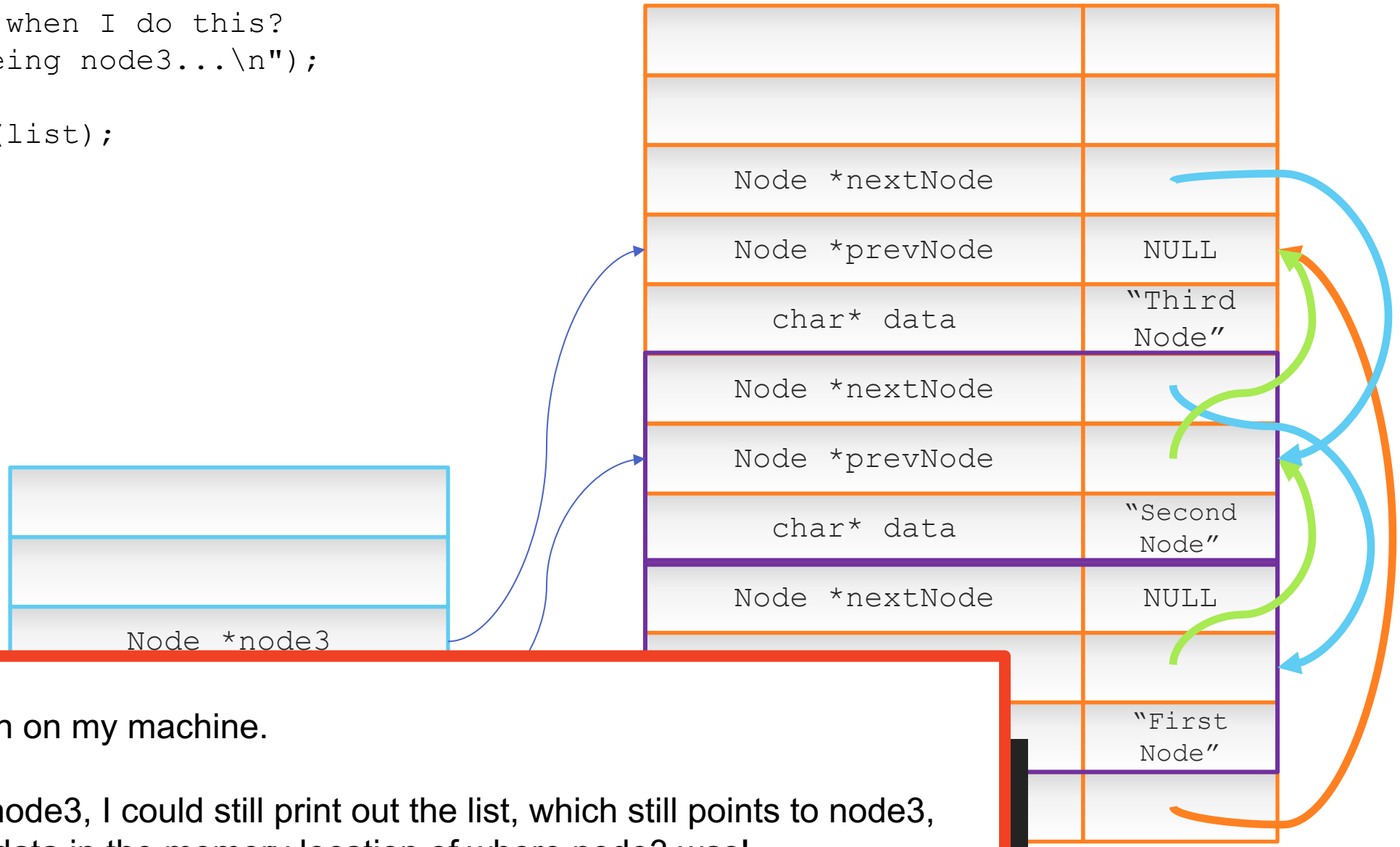

**Stack**
(Memory, not the data structure)




**Heap**
(Memory, not the data structure)

```
        …
        // Continuing on…
        // What happens when I do this?
        printf("I'm freeing node3...\n");
        free(node3);
        printLinkedList(list);

}
```




Once again, the code I ran on my machine.

We see that after I freed node3, I could still print out the list, which still points to node3, and I can still access the data in the memory location of where node3 was!

free() is only guaranteed to ***not save that chunk of memory*** any more. It doesn't

structure)

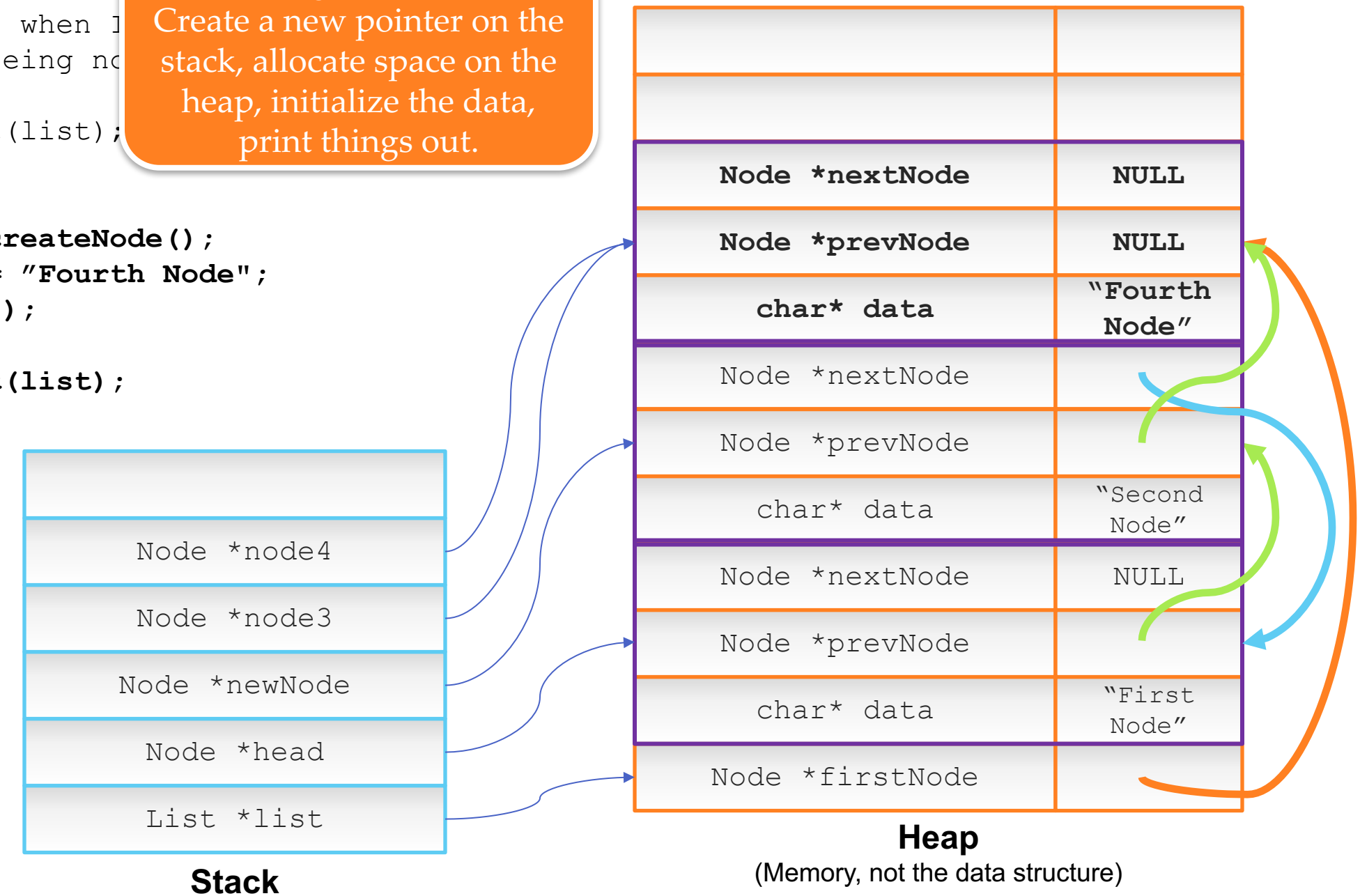
```
…
// Continuing on…
// What happens when I
printf("I'm freeing no
free(node3);
printLinkedList(list);

// But now…
Node *node4 = createNode();
node4 -> data = "Fourth Node";
printNode(node4);

printLinkedList(list);
```

}

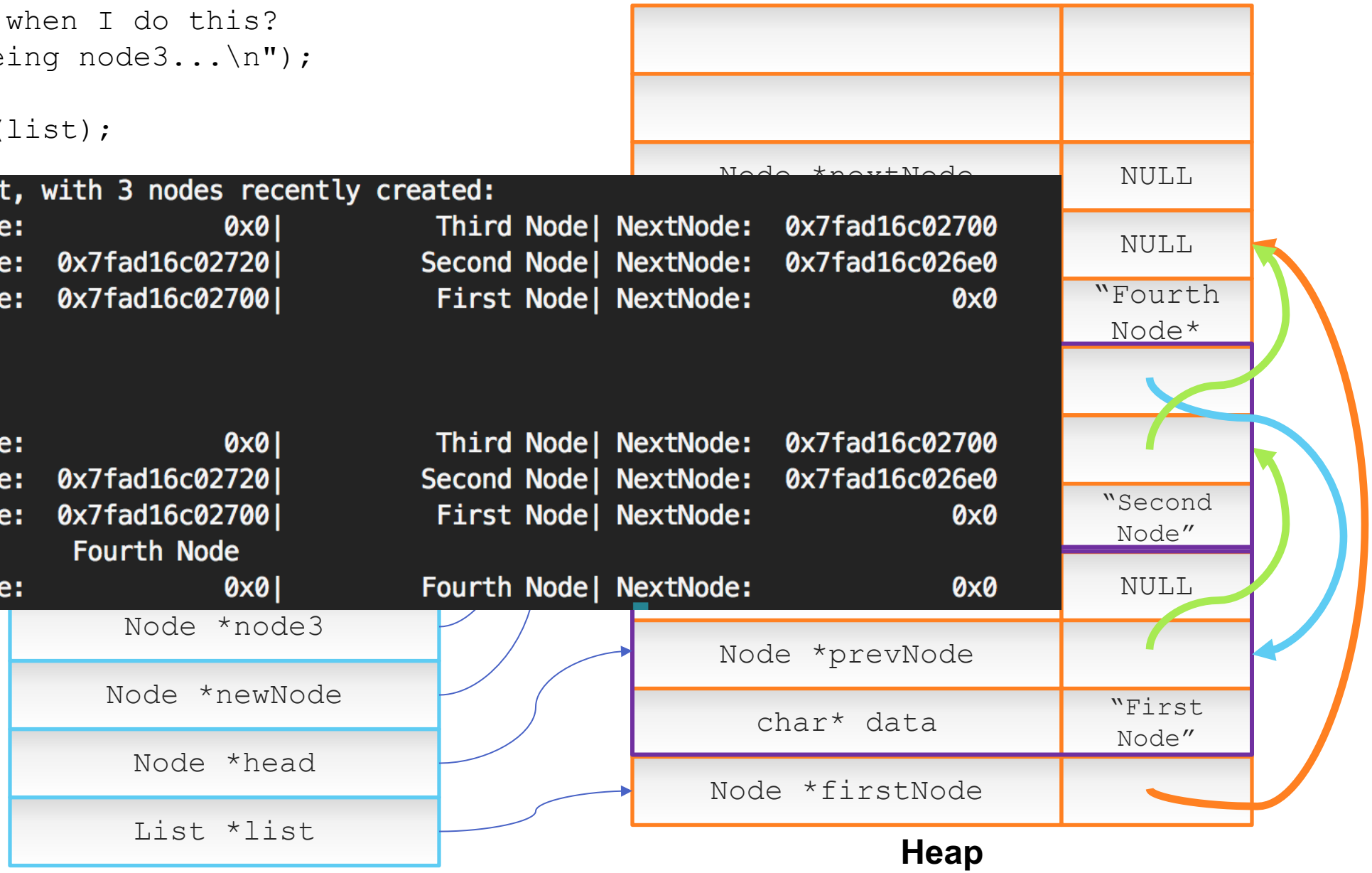
Creating a new node. Create a new pointer on the stack, allocate space on the heap, initialize the data, print things out.



```
    …
    // Continuing on…
    // What happens when I do this?
    printf("I'm freeing node3...\n");
    free(node3);
    printLinkedList(list);
}
```

```
printing the linked list, with 3 nodes recently created:
0x7fad16c02720  PrevNode:                0x0|          Third Node| NextNode:  0x7fad16c02700
0x7fad16c02700  PrevNode:  0x7fad16c02720|         Second Node| NextNode:  0x7fad16c026e0
0x7fad16c026e0  PrevNode:  0x7fad16c02700|          First Node| NextNode:              0x0

-------
I'm freeing node3...
0x7fad16c02720  PrevNode:                0x0|          Third Node| NextNode:  0x7fad16c02700
0x7fad16c02700  PrevNode:  0x7fad16c02720|         Second Node| NextNode:  0x7fad16c026e0
0x7fad16c026e0  PrevNode:  0x7fad16c02700|          First Node| NextNode:              0x0
Node: 0x7fad16c02720         Fourth Node
0x7fad16c02720  PrevNode:                0x0|         Fourth Node| NextNode:              0x0
```



```
…
// Continuing on…
// What happens when I do this?
printf("I'm freeing node3...\n");
free(node3);
printLinkedList(list);

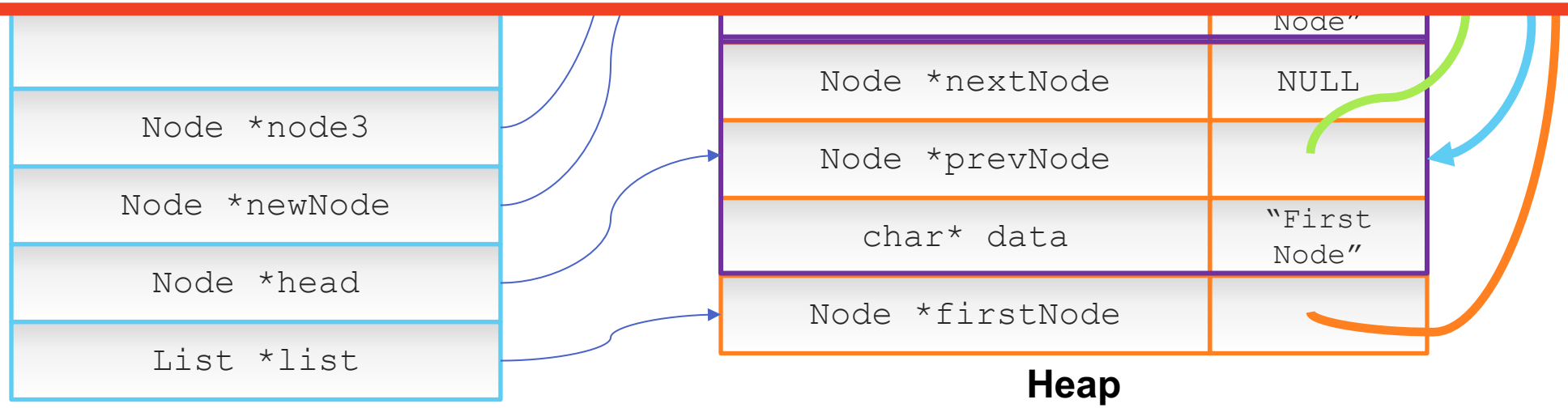
// But now…
```

Now, all of the above I ran on one machine.

I very particularly did this to demonstrate these concepts.

The fact is: you can't assume that all systems will behave like this.

I ran this same code on a different machine/different version of C, and it gave me a seg fault.



# To Summarize:

- **malloc** allocates some space on the heap
  - Until it's been freed, the heap is not going to put anything else in there.
- **free** de-allocates that space on the heap.
  - Nothing else is promised.
  - It does not guarantee that anything is removed from that memory.
  - It does not guarantee that you don't still have pointers to it.
- Unless you specifically clear out the memory, you can still access the data in that memory.
- But you can't ***guarantee*** access to that data.
- *Anyone smell potential threats to data???*

# DATA STRUCTURES INTRO

# What is a Data Structure?

- A structure used to store data.
  - Stores data called elements
  - Typical operations:
    - add()
    - remove()
    - clear()
    - size()
    - contains()
    - isEmpty()

# Examples of data structures

- Stack
- Lists (Array, Linked)
- Queue
- Maps
- Sets
- Trees

**Why so many?**

http://diaryofafitmommy.com/chocolate-chip-cookie-dough-protein-bites/#
https://www.amazon.com/Betty-Crocker-3-in-1-Baking-Rack/dp/B0018DYW84
http://i693.photobucket.com/albums/vv298/theliebertfamily/oct12/chewy-molasses-spice-cookies-400_zpsb89ed2fa.jpg

## Set

## Queue

## Stack

http://diaryofafitmommy.com/chocolate-chip-cookie-dough-protein-bites/#
https://www.amazon.com/Betty-Crocker-3-in-1-Baking-Rack/dp/B0018DYW84
http://i693.photobucket.com/albums/vv298/theliebertfamily/oct12/chewy-molasses-spice-cookies-400_zpsb89ed2fa.jpg

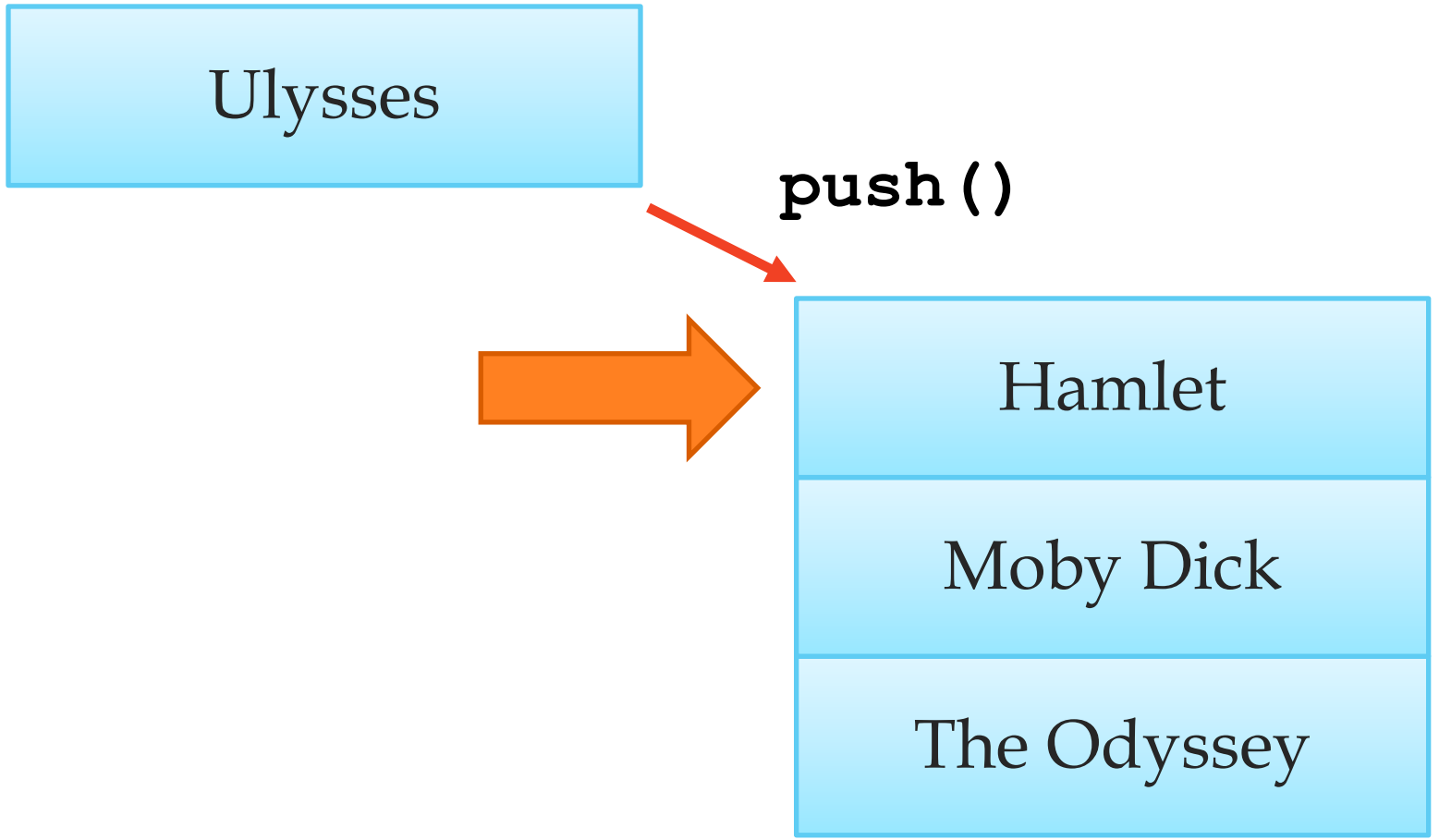
# Eventually, we will:

- Compare data structures based on:
  - **Characteristics**
    - LIFO? FIFO? Random Access? Can there be many copies of an element?
  - **Operations** we can perform on a data structure
  - **Performance and efficiency**:
    - How long does it take to put a piece of data in a data structure?
    - How long does it take to get data out of a data structure?
    - How much memory does the data structure use?

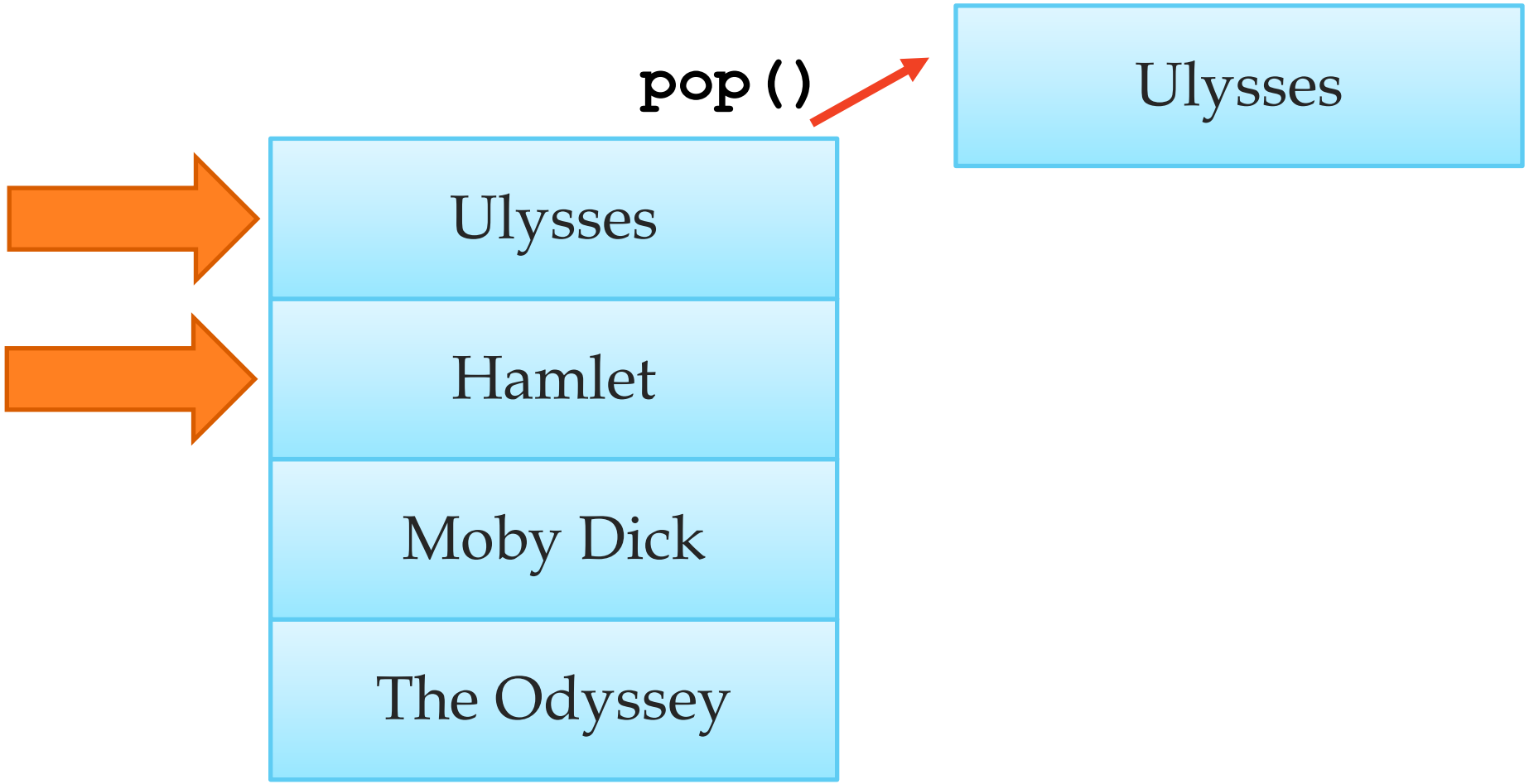
# STARTING WITH STACKS…

https://www.istockphoto.com/photo/stack-of-books-isolated-on-white-background-gm514536119-47608274

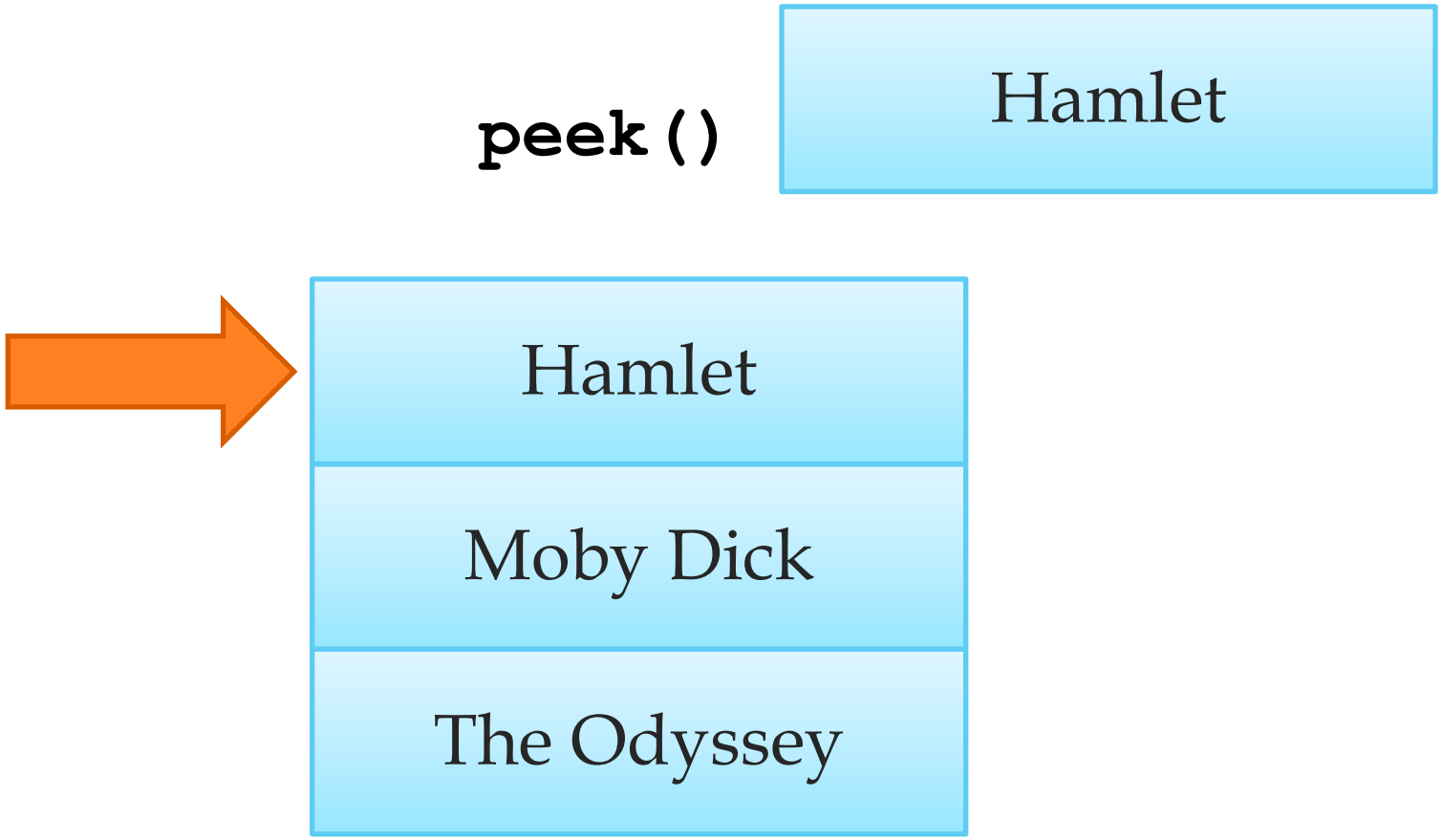
# What is a stack?



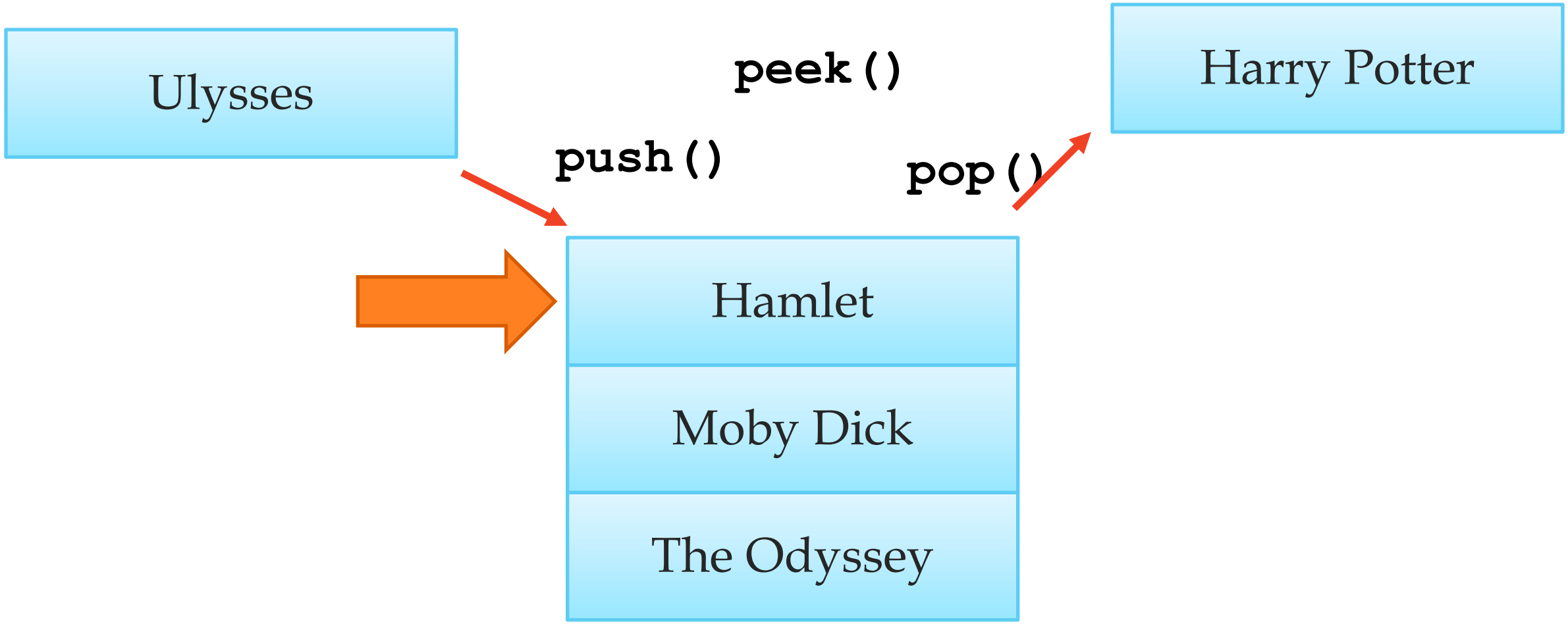
# What is a stack?



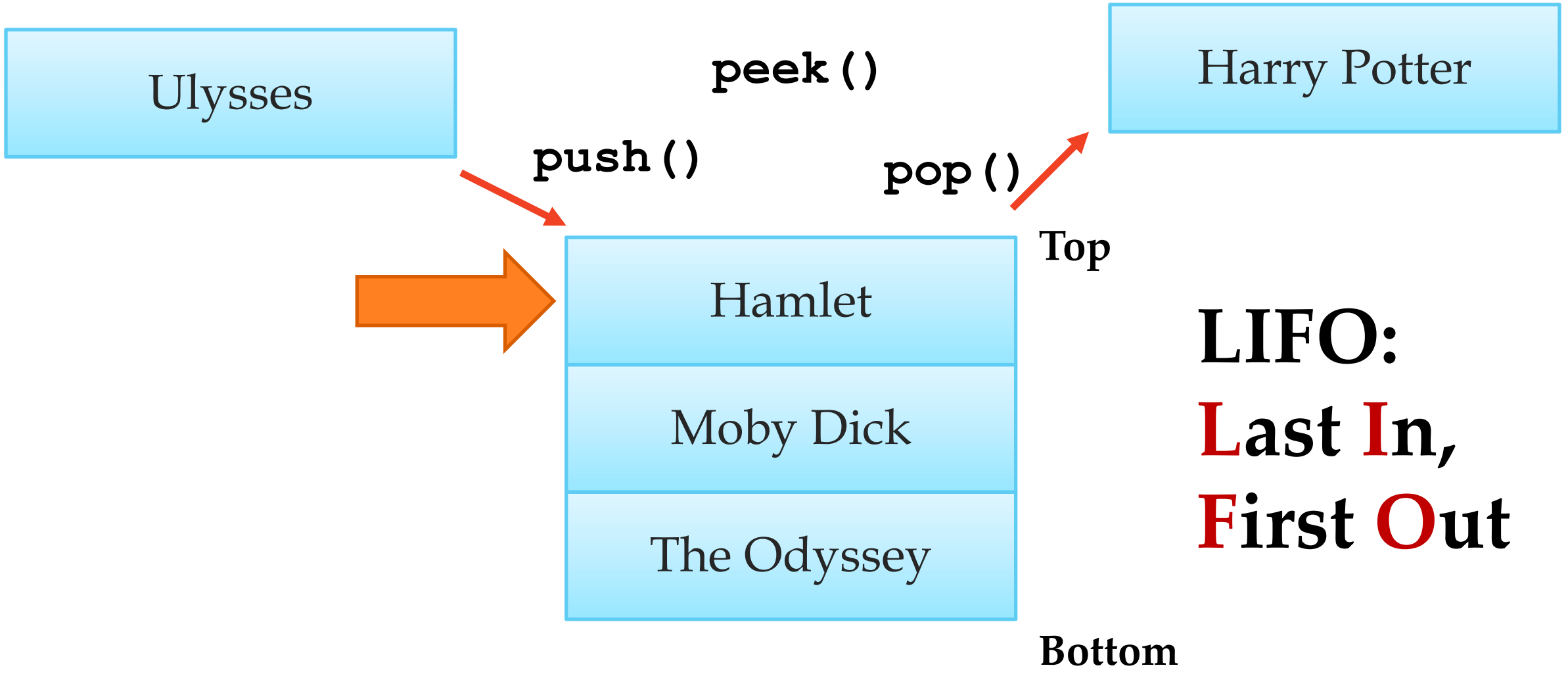
# What is a stack?



# What is a stack?



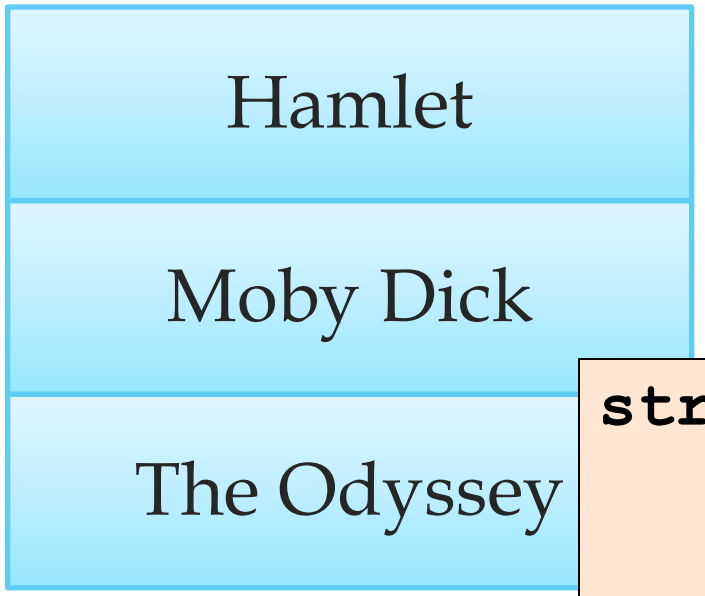
# What is a stack?




**LIFO:**
**Last In,**
**First Out**

# What is a stack in C?

```
int bookAtTop;
```




```
char* booknames[];
```

```
struct StackOfBooks{
    char* booknames[SIZE];
    int bookAtTop;
}
```

# Stack Operations

- pop()
- push()
- peek()
- create()
- destroy()

# Stack Operations in C

- `char* pop(stackOfBooks*);`
- `stackOfBooks* push(char* newBook, stackOfBooks*);`
- `char* peek(stackOfBooks*);`
- `stackOfBooks* create();`
- `void destroy(stackOfBooks*);`

```
struct stackOfBooks{
    char* booknames[SIZE];
    int bookAtTop;
}
```

# Implementing Stack Operations in C: create()

- `stackOfBooks* create();`

```
stackOfBooks* create(){
        // Allocate space on the heap
        stackOfBooks* newStack =
                (stackOfBooks*)malloc(sizeof(stackOfBooks));
        // Initialize anything
        newStack->bookAtTop = -1;
        // Return pointer to new stack
        return newStack;
}
```

```
struct stackOfBooks{
    char* booknames[SIZE];
    int bookAtTop;
}
```

# Implementing Stack Operations in C: destroy()

- `void destroy(stackOfBooks*);`

```
void destroy(stackOfBooks* bookStack){
      // Free anything that hasn't been freed

      // Free the stack
      free(bookStack);
}
```

```
struct stackOfBooks{
   char* booknames[SIZE];
   int bookAtTop;
}
```

# Implementing Stack Operations in C: push()

- `stackOfBooks* push(char*, stackOfBooks*);`

```
stackOfBooks* push(char* newBook, stackOfBooks* bookStack){
        // Update the head index
        bookStack->bookAtTop++;

        // Put the element in the array
        bookStack->booknames[WHAT GOES HERE] = newBook;

        // Return stack (by convention)
        return bookStack;
}
```

```
struct stackOfBooks{
    char* booknames[SIZE];
    int bookAtTop;
}
```

# Implementing Stack Operations in C: push()

- `stackOfBooks* push(char*, stackOfBooks*);`

```
stackOfBooks* push(char* newBook, stackOfBooks* bookStack){
        // Update the head index
        bookStack->bookAtTop++;

        // Put the element in the array
        bookStack->booknames[bookstack->bookAtTop] = newBook;

        // Return stack (by convention)
        return bookStack;
}
```

```
struct stackOfBooks{
    char* booknames[SIZE];
    int bookAtTop;
}
```

# Implementing Stack Operations in C: pop()

- `char* pop(stackOfBooks*);`

```
char* pop(stackOfBooks* bookStack){
      // Get the element from the array
      return bookStack->booknames[WHAT GOES HERE];

      // Update the head index???
}
```

```
struct stackOfBooks{
   char* booknames[SIZE];
   int bookAtTop;
}
```

# Implementing Stack Operations in C: pop()

- `char* pop(stackOfBooks*);`

```
char* pop(stackOfBooks* bookStack){
      // Get the element from the array
      return bookStack->booknames[bookStack->bookAtTop--];

      // Update the head index???
}
```

```
struct stackOfBooks{
   char* booknames[SIZE];
   int bookAtTop;
}
```

# Implementing Stack Operations in C: peek()

- `char* peek(stackOfBooks*);`

```
char* peek(stackOfBooks* bookStack){
      // Get the element from the array
      return bookStack->booknames[WHAT GOES HERE];

      // Update the head index???
}
```

```
struct stackOfBooks{
   char* booknames[SIZE];
   int bookAtTop;
}
```

# Implementing Stack Operations in C: peek()

- `char* peek(stackOfBooks*);`

```
char* peek(stackOfBooks* bookStack){
      // Get the element from the array
      return bookStack->booknames[bookStack->bookAtTop];

      // Update the head index???
}
```

```
struct stackOfBooks{
   char* booknames[SIZE];
   int bookAtTop;
}
```

# Let's play with code…

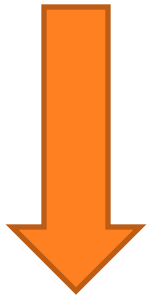
- https://github.ccs.neu.edu/CS5002SEAF17/resources/blob/master/lect9/stack_play.c

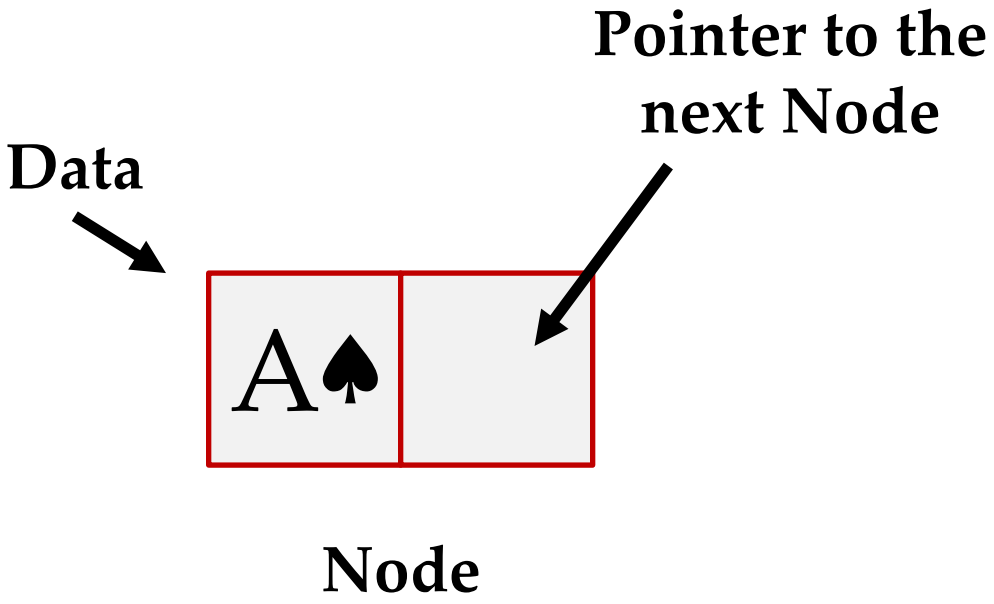
- (CS5002 resources repo on github; lect9)

# PLAYING WITH LINKED LISTS

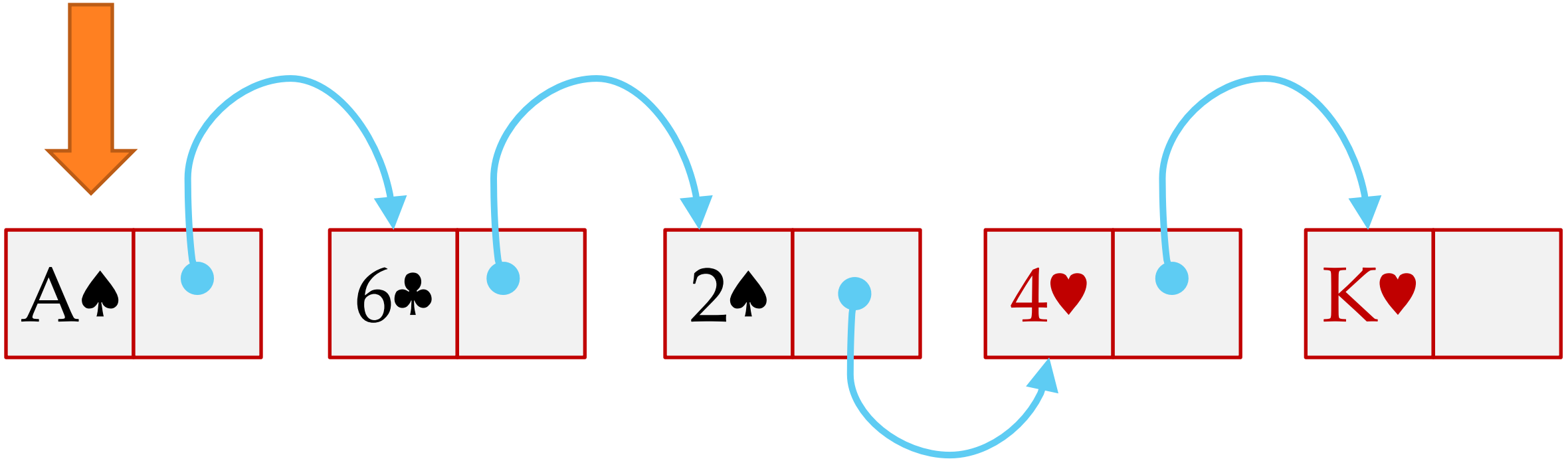
# Okay, back to the fun stuff.

# What is a Linked List?

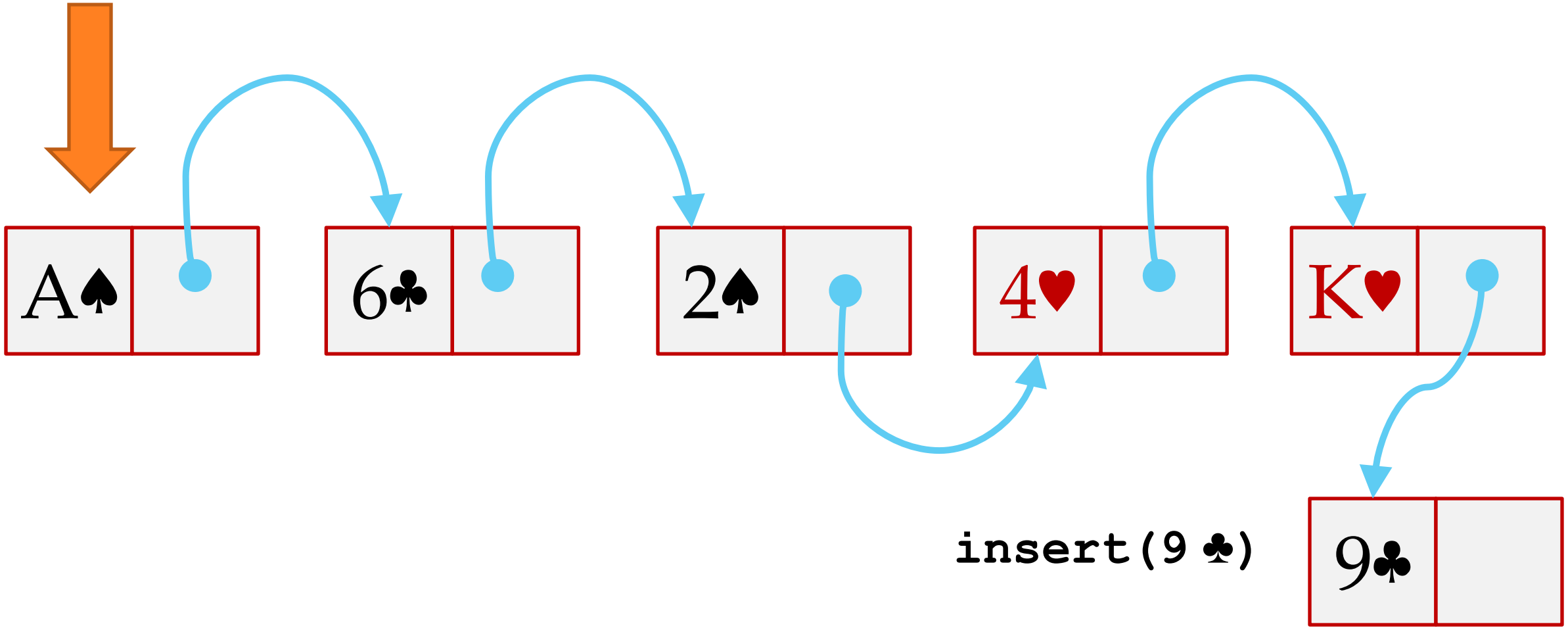




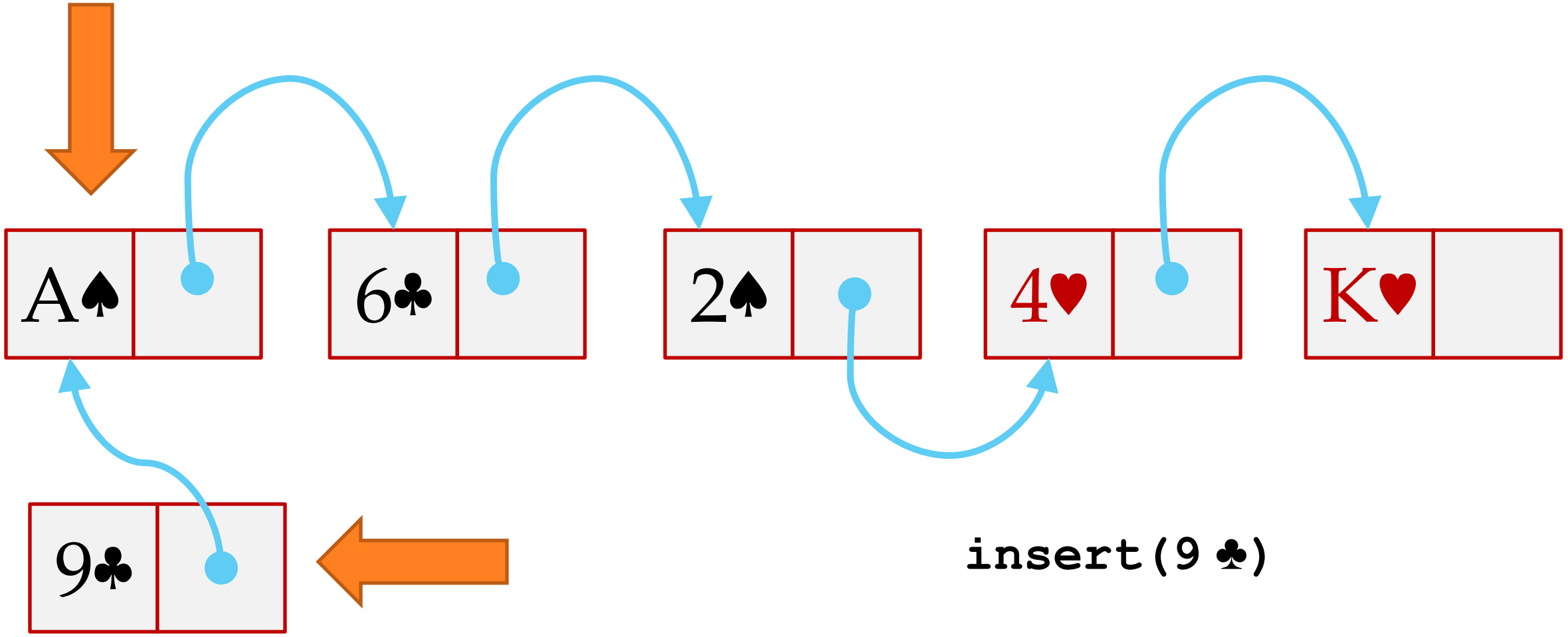
# What is a Linked List?



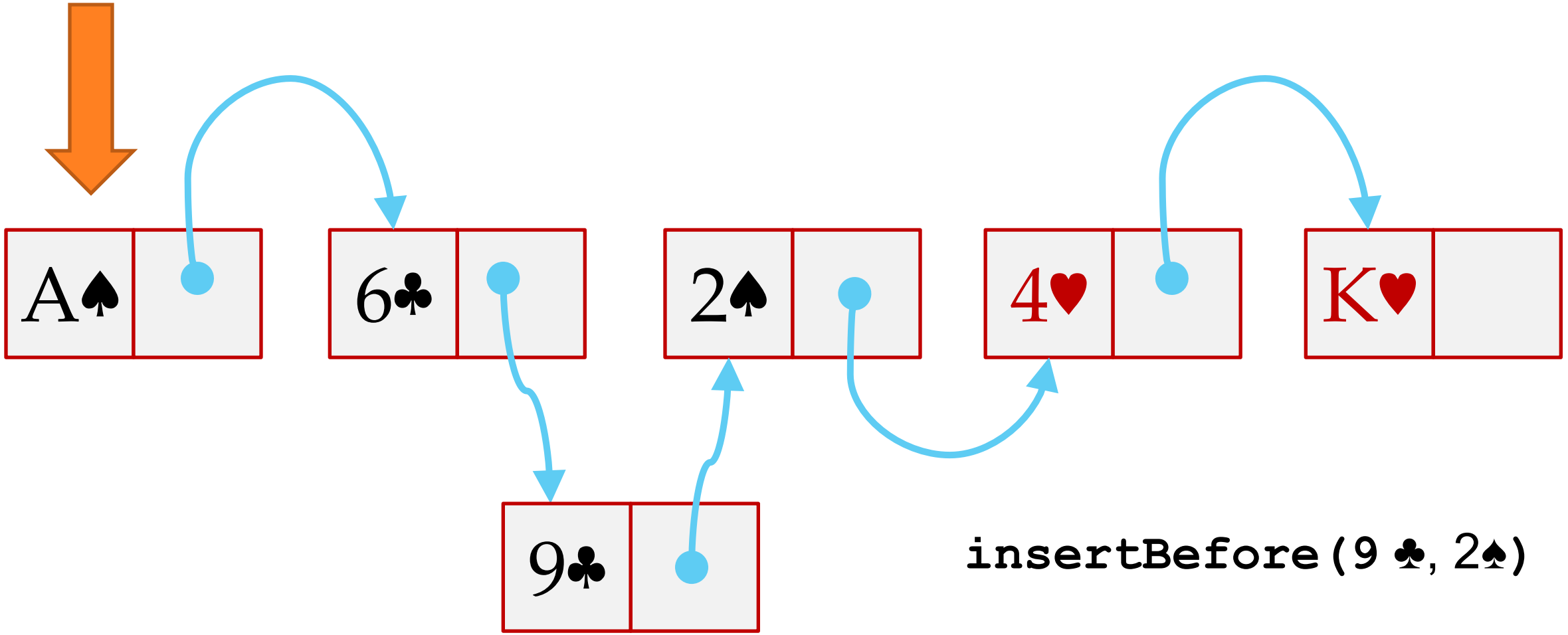
# Adding a Node to a Linked List



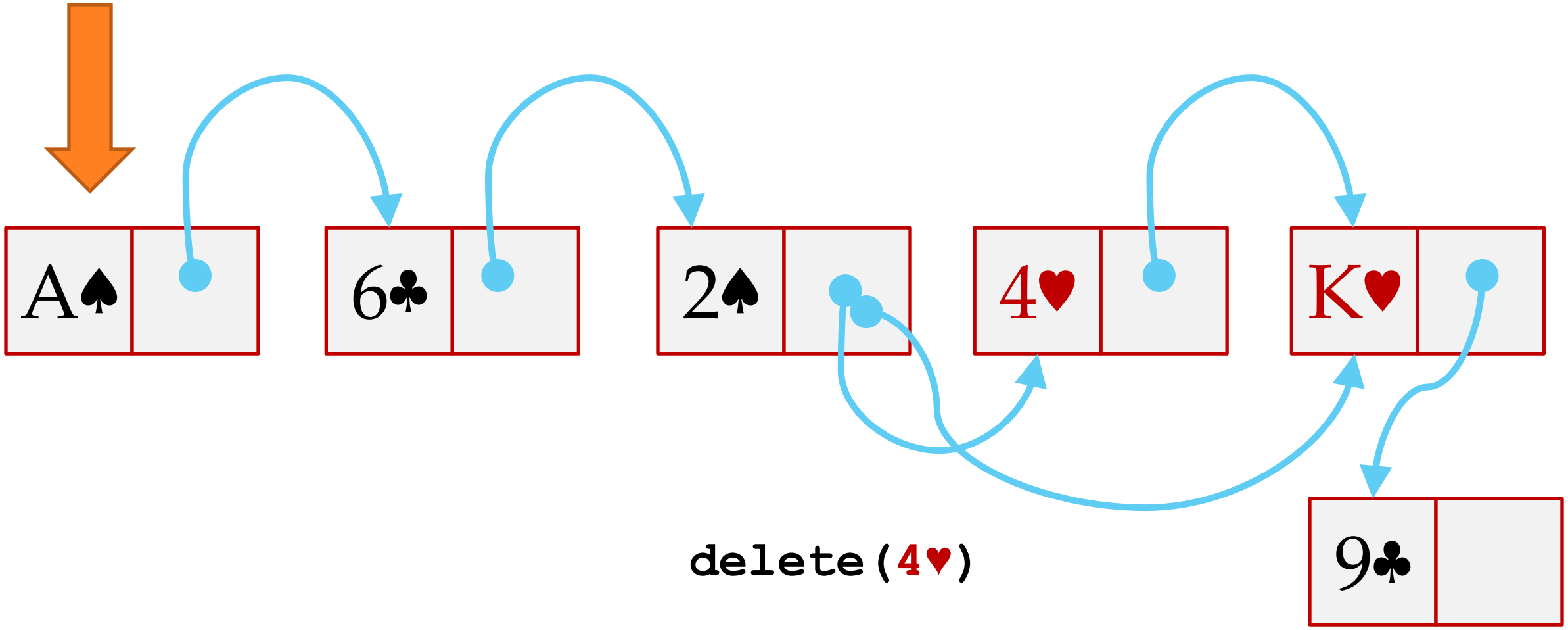
# An Alternative Way to Add a Node



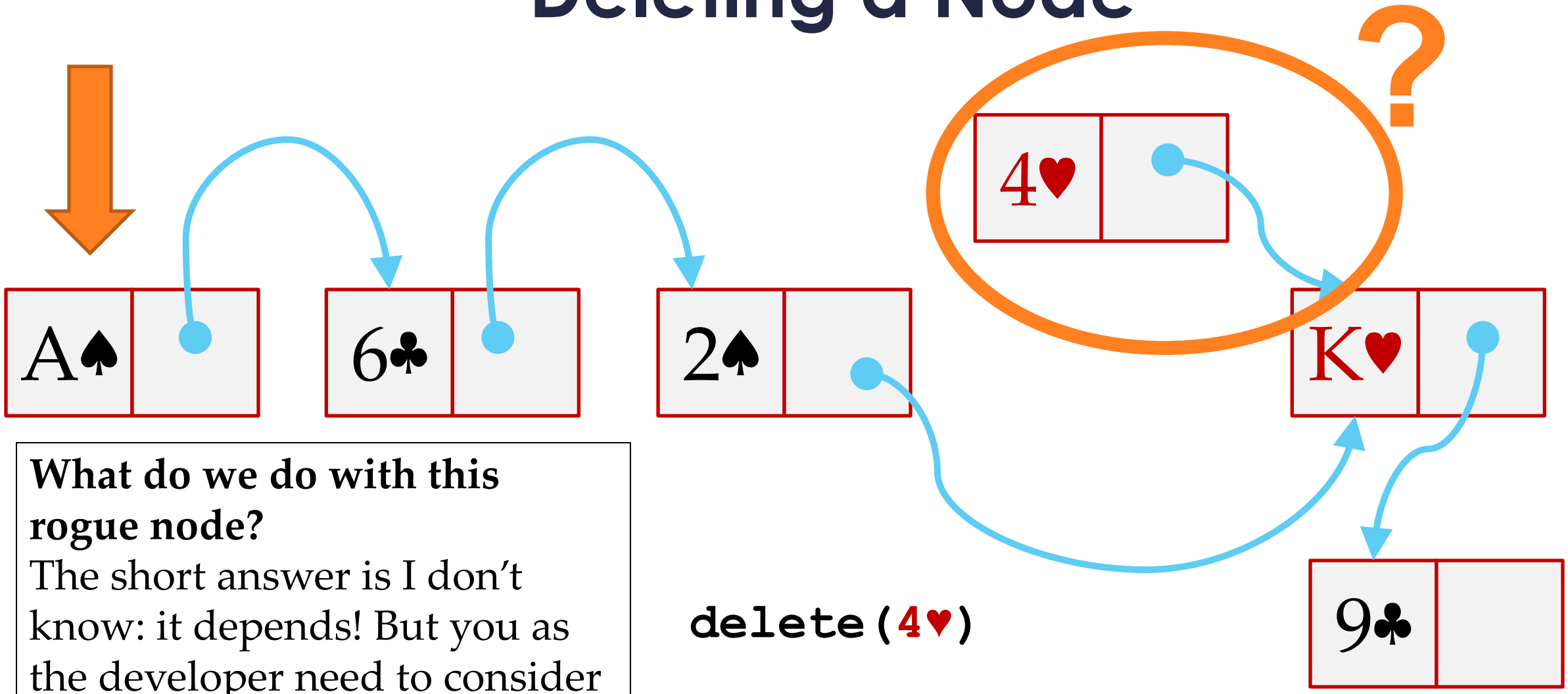
# Another Alternative Way to Add a Node



# Deleting a Node



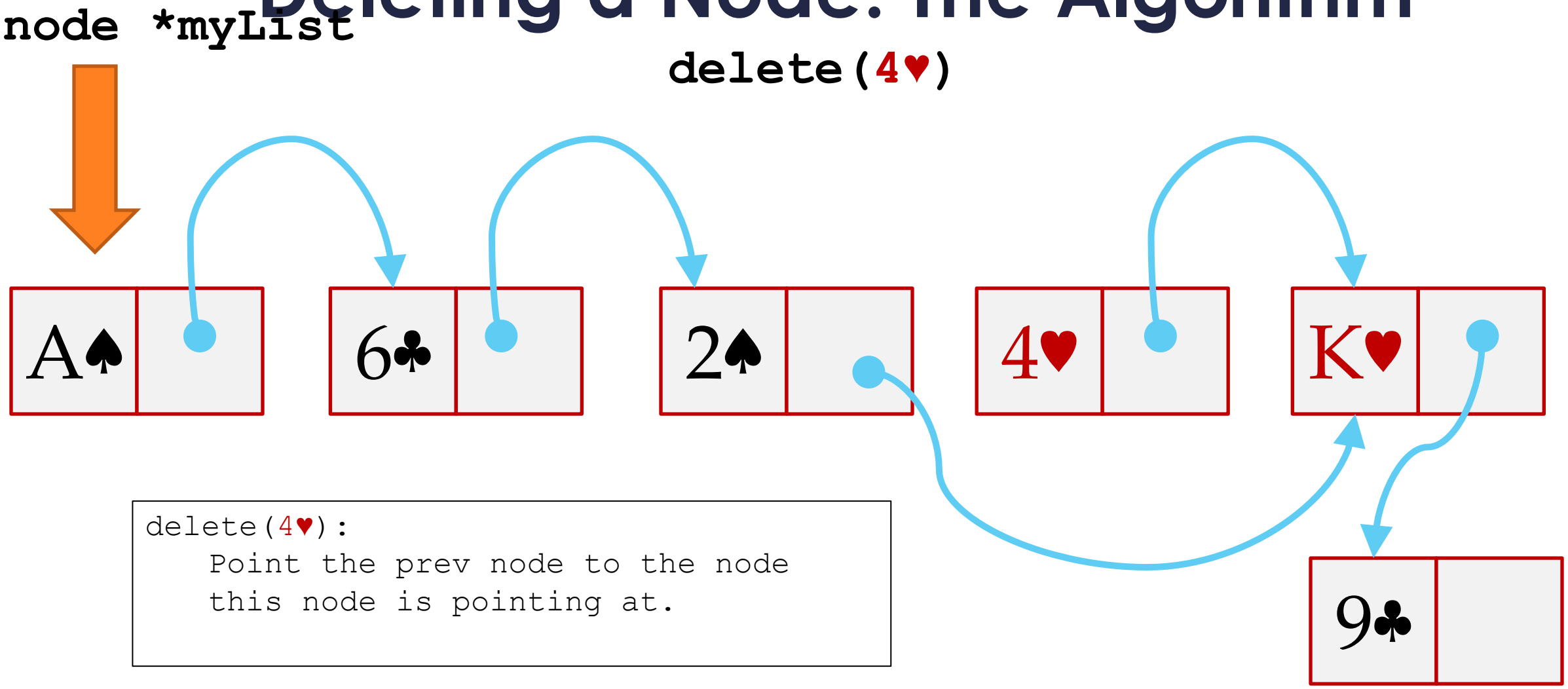
# Deleting a Node




**What do we do with this rogue node?**

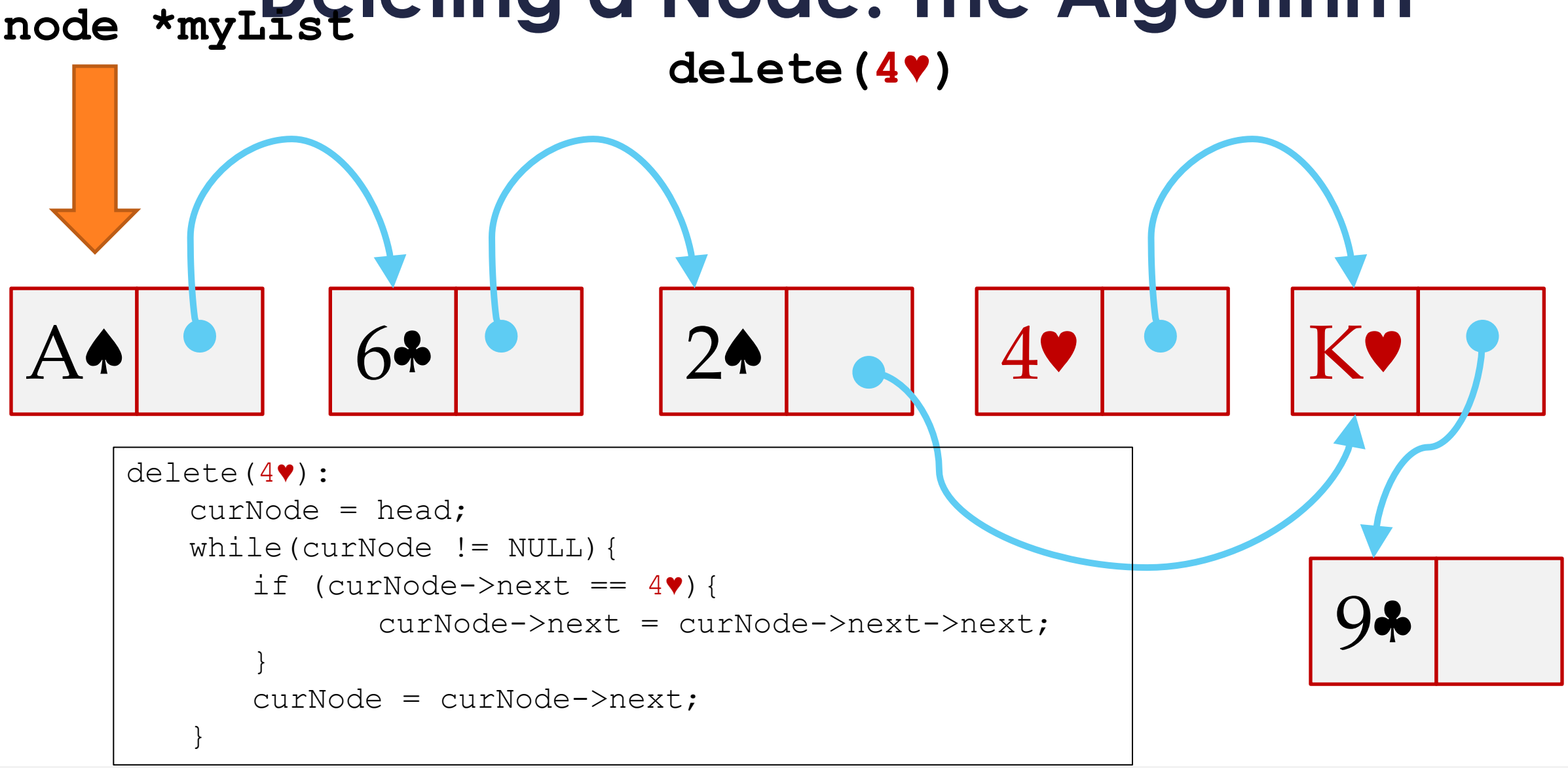
The short answer is I don't know: it depends! But you as the developer need to consider when it gets freed from the heap.

# Deleting a Node: The Algorithm




```
delete(4♥):
    Point the prev node to the node
    this node is pointing at.
```

# Deleting a Node: The Algorithm



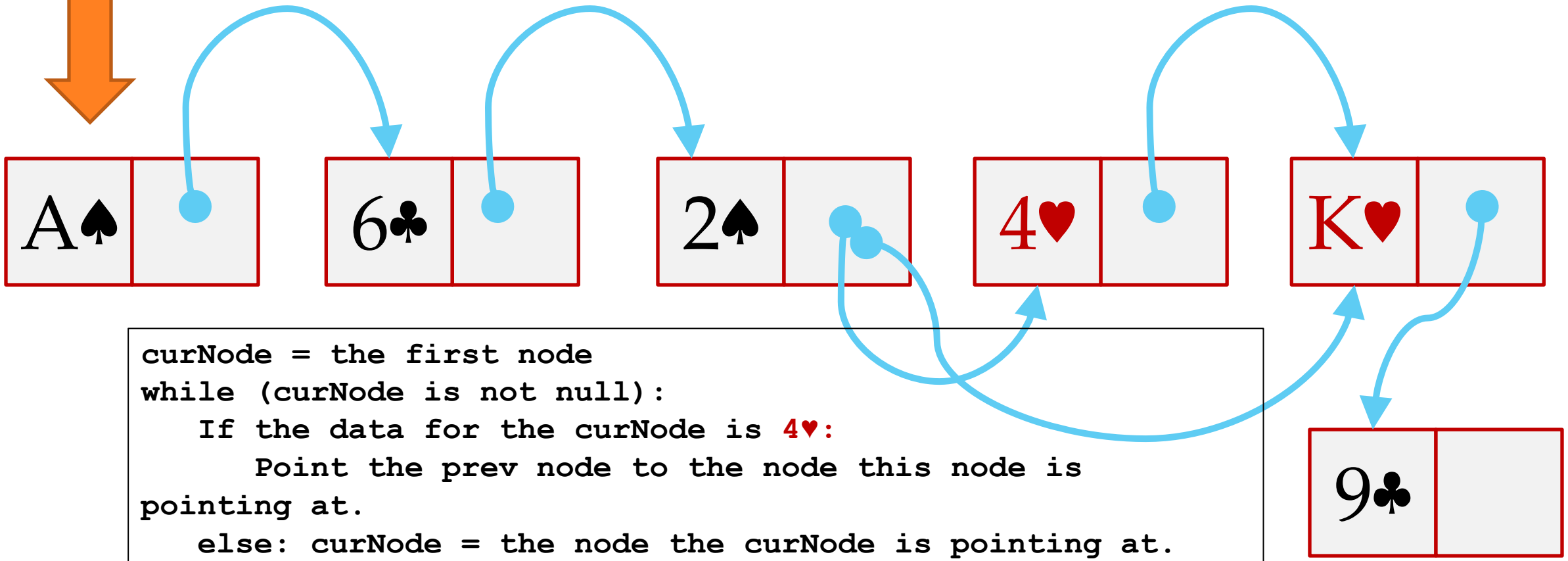

```
delete(4♥):
    curNode = head;
    while(curNode != NULL){
        if (curNode->next == 4♥){
                curNode->next = curNode->next->next;
        }
        curNode = curNode->next;
    }
```

What if I know which
***data*** I want to remove
(4♥),
but I don't know which
***NODE*** it is?

# Deleting a Node: The Algorithm

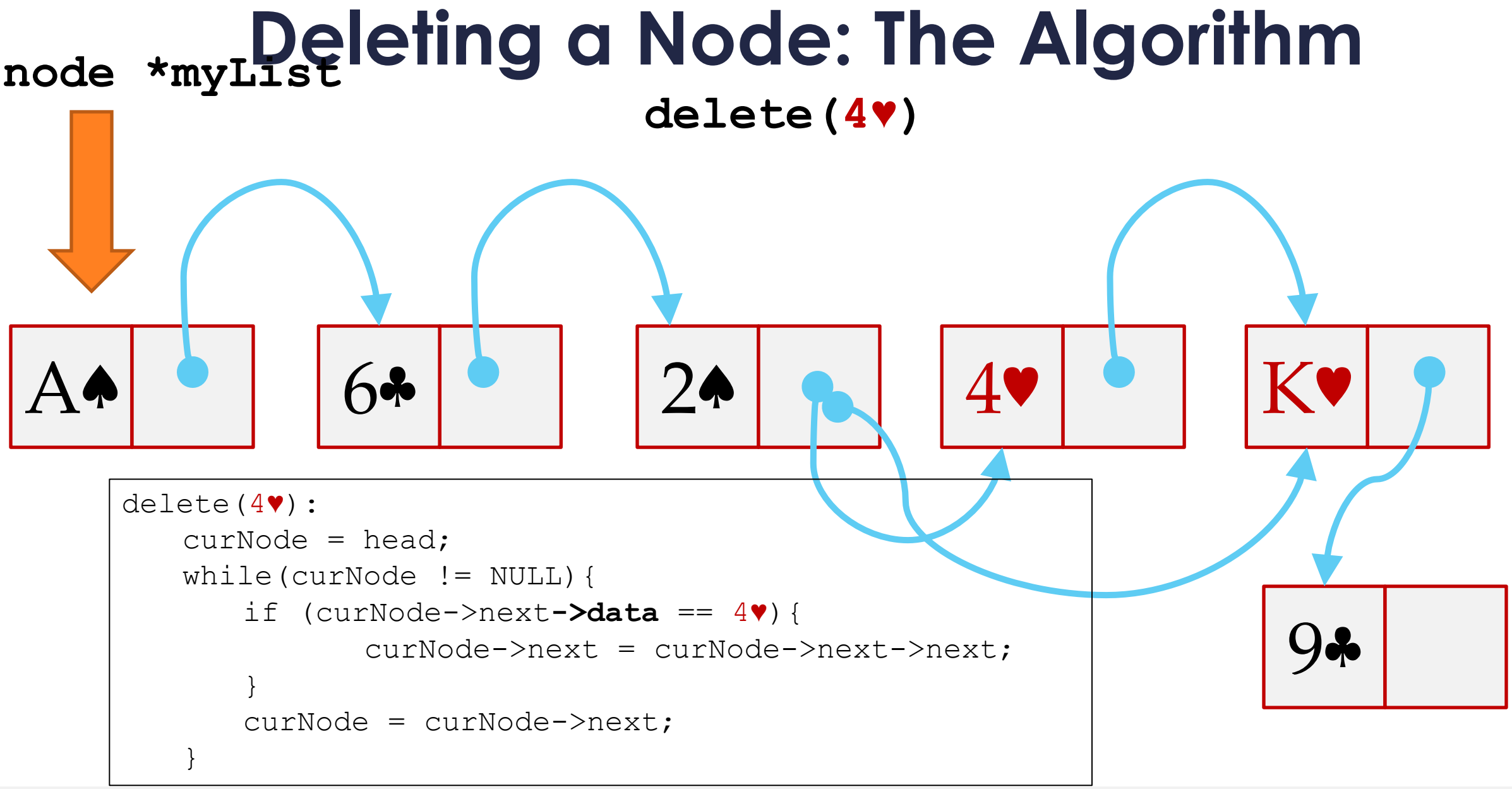
`node *myList`

`delete(4♥)`




```
curNode = the first node
while (curNode is not null):
   If the data for the curNode is 4♥:
      Point the prev node to the node this node is
pointing at.
   else: curNode = the node the curNode is pointing at.
```

# Deleting a Node: The Algorithm

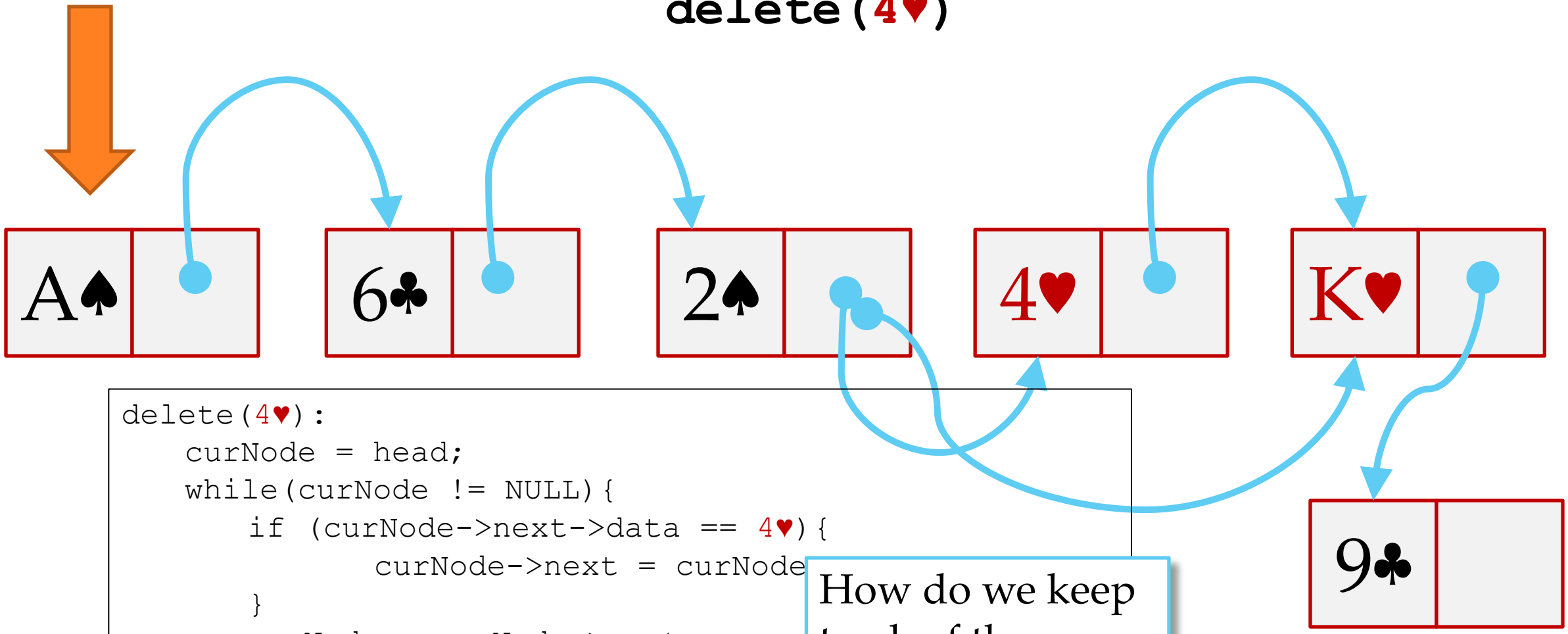



```
delete(4♥):
    curNode = head;
    while(curNode != NULL){
        if (curNode->next->data == 4♥){
                curNode->next = curNode->next->next;
        }
        curNode = curNode->next;
    }
```

# Deleting a Node: The Algorithm

`node *myList`

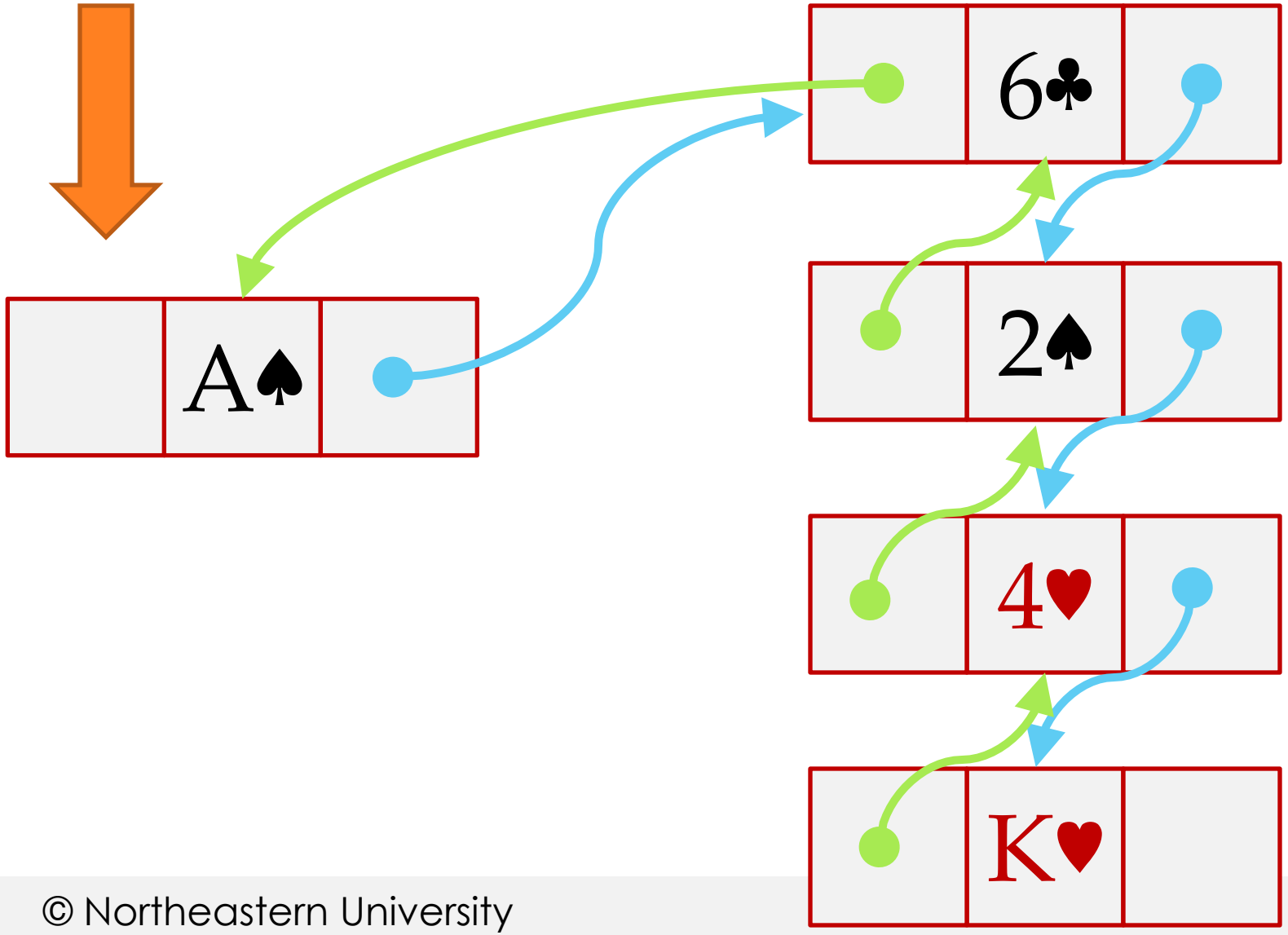
`delete(4♥)`




```
delete(4♥):
    curNode = head;
    while(curNode != NULL){
        if (curNode->next->data == 4♥){
                curNode->next = curNode
        }
        curNode = curNode->next;
    }
```

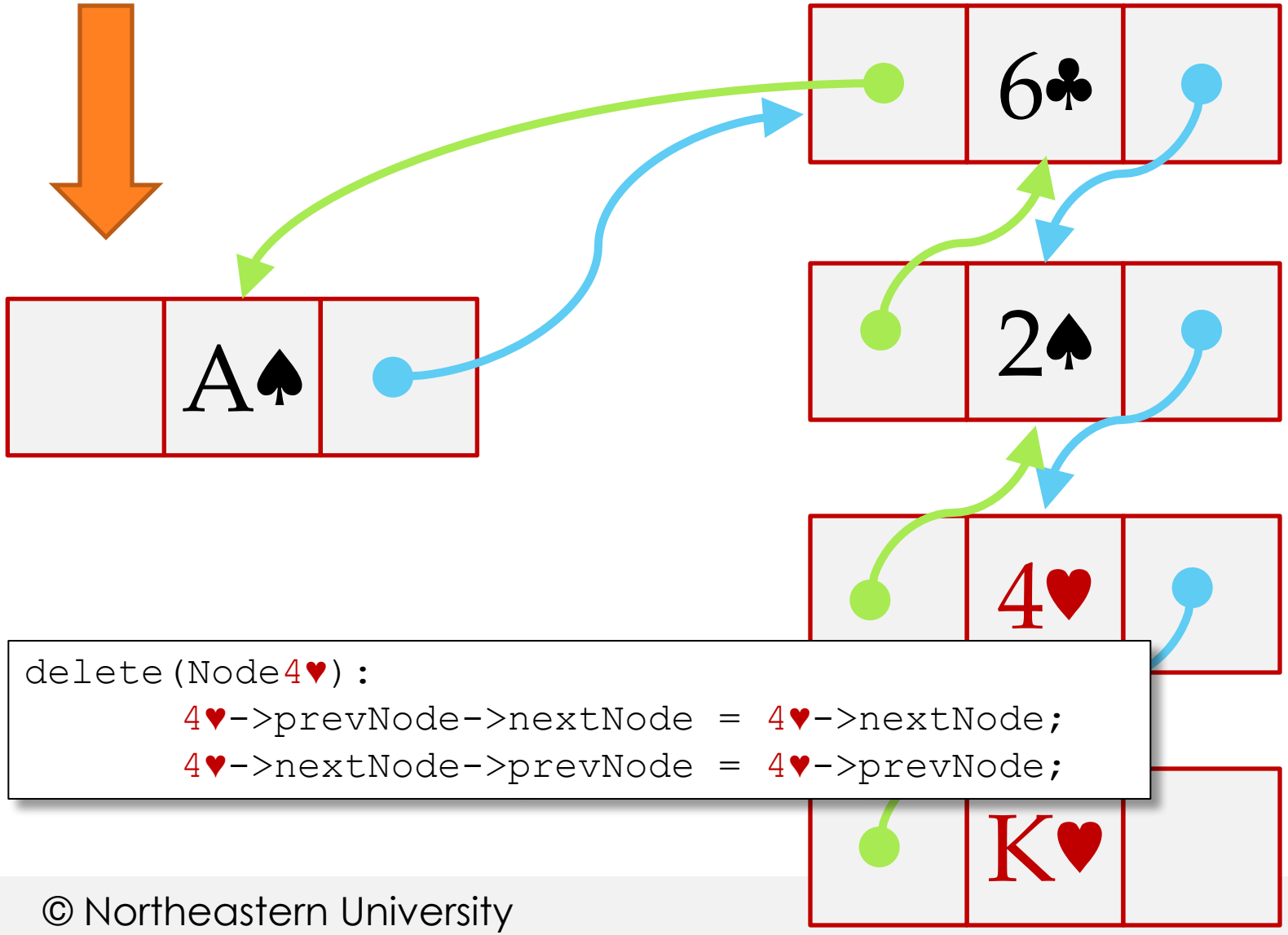
How do we keep track of the previous node??

# Solving some problems: a Doubly Linked List




```
struct Node{
    char* data;
    Node* prevNode;
    Node* nextNode;
};
```

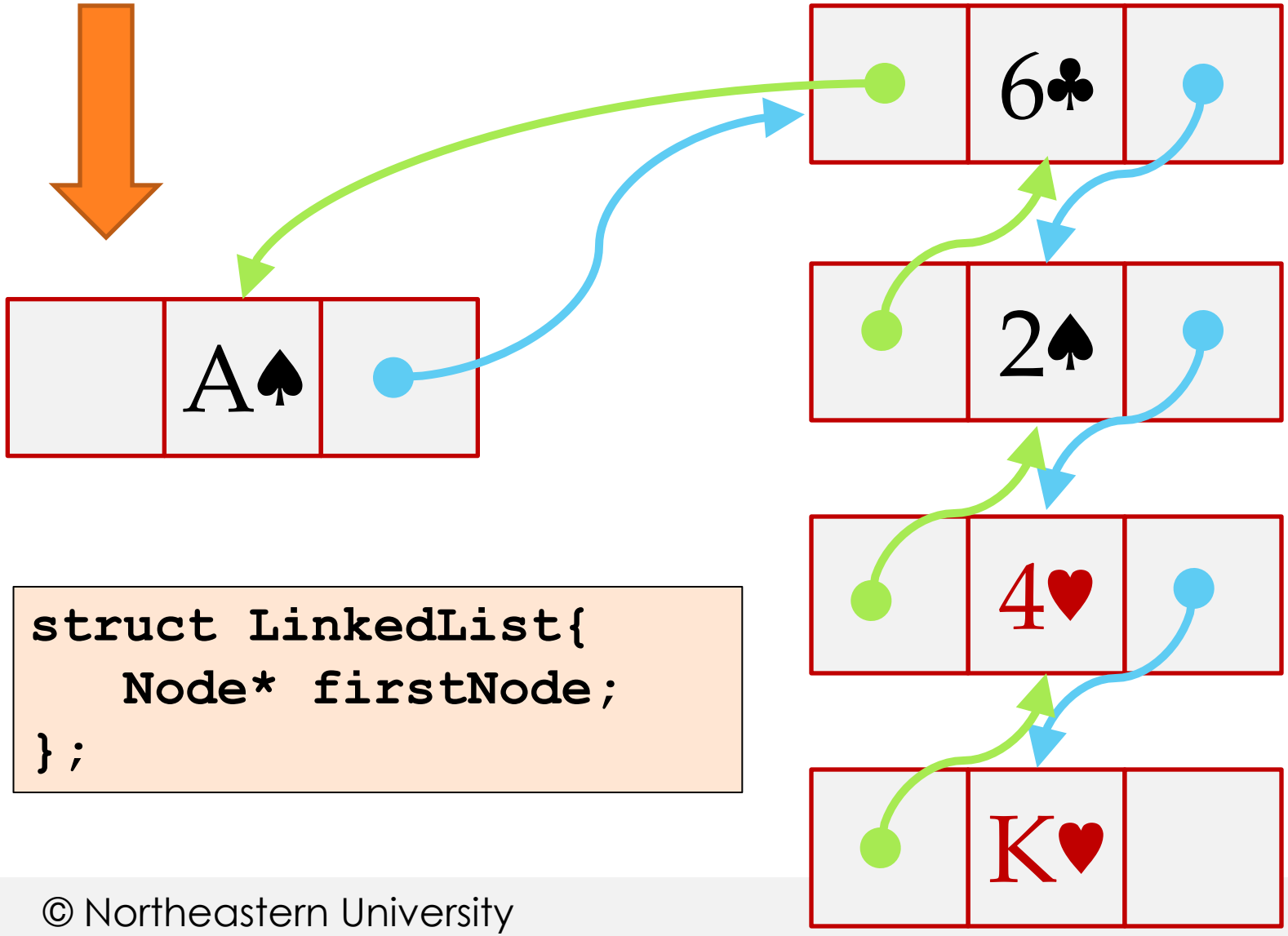
# Solving some problems: a Doubly Linked List




```
delete(Node4♥):
        4♥->prevNode->nextNode = 4♥->nextNode;
        4♥->nextNode->prevNode = 4♥->prevNode;
```

```
struct Node{
    char* data;
    Node* prevNode;
    Node* nextNode;
};
```

# Solving some problems: a Doubly Linked List




```
struct LinkedList{
    Node* firstNode;
};
```

```
struct Node{
    char* data;
    Node* prevNode;
    Node* nextNode;
};
```

**For the rest of this lecture, we're going to focus on:**
*** Doubly Linked List**
*** List is a special struct with the head of the list**

# Linked List Operations

- insert() or add()
- remove()
- create()
- destroy()
- contains()
- isEmpty()
- -----
- iterating: a helpful pattern

# Linked List Operations in C

- `void insert(list*, node*)`
- `void remove(list*, node*)`
- `list* create()`
- `void destroy(list*)`
- `int contains(list*, node*)`
- `int isEmpty(list*)`

# Linked List Operations in C: createList()

- `list* create()`

```
list* create(){
    list* list = (list*)malloc(sizeof(list));
    return list;
}
```

```
struct Node{
    char* data;
    Node* prevNode;
    Node* nextNode;
};
```

# Linked List Operations in C: createNode()

- `node* createNode(char* data)`

```
node* createNode(char* data){
    node* node = (node*)malloc(sizeof(node));
    node->data =  data;
    node->prevNode = NULL;
    node->nextNode = NULL;
    return node;
}
```

```
struct Node{
    char* data;
    Node* prevNode;
    Node* nextNode;
};
```

# Linked List Operations in C: destroy()

- `void destroy(list*)`

```
void destroy(list* aList){
    // What to do with this Node?
    // What if the list is not empty???
    free(aList->firstNode); // Should I do this?
    free(aList);
}
```

```
struct Node{
    char* data;
    Node* prevNode;
    Node* nextNode;
};
```

# Linked List Operations in C: insert ()

```
struct Node{
    char* data;
    Node* prevNode;
    Node* nextNode;
};
```

- `void insert(list*, node*)`

```
// inserting at the front of the list
void insert(list* aList, node *newNode){
        if(aList->firstNode != NULL){
                // Point the new node to the first node
                newNode->nextNode = aList->firstNode;
                // Point it back
                aList->firstNode->prevNode = newNode;
        }
        // Return the now-first element of the list
        aList->firstNode = newNode;
}
```

# Linked List Operations in C: insert ()

- `node* insertAtEnd(list*, node*)`

```
// inserting at the end of the list
node* insertAtEnd(node* aList, node *newNode){
      ** WRITE THIS CODE **
}
```

```
struct Node{
    char* data;
    Node* prevNode;
    Node* nextNode;
};
```

# Linked List Operations in C: remove ()

- `void remove(list*, node*)`

```
void remove(node* aList, node* aNode){
    if(aNode->prevNode != NULL){
        aNode->prevNode->nextNode = aNode->nextNode;
    }
    if(aNode->nextNode != NULL){
        aNode->nextNode->prevNode = aNode->prevNode;
    }
}
```

**What do we do with this rogue node?**
The short answer is I don't know: it depends! But you as the developer need to consider when it gets freed from the heap.

```
struct Node{
    char* data;
    Node* prevNode;
    Node* nextNode;
};
```

# Linked List Operations in C: contains()

- `int contains(list*, node*)`

```
int contains(list* aList, node* aNode){
    ** WRITE THIS CODE **
}
```

```
struct Node{
    char* data;
    Node* prevNode;
    Node* nextNode;
};
```

# Linked List Operations in C: containsValue()

- `int containsValue(list*, data);`

```
int containsValue(list* aList, char* data){
    ** WRITE THIS CODE **
}
```

**What to return?**
0/1 for True/False?
Or the Node containing the data?

```
struct Node{
    char* data;
    Node* prevNode;
    Node* nextNode;
};
```

# Let's Play with Code...

- https://github.ccs.neu.edu/CS5002SEAF17/resources/tree/master/lect9

- Github->CS5002SEAF17-> resources->lect9-> linked_list.c

# Arrays Versus LinkedList

**Array**

- Contiguous Memory
- You have to know the size before you create it
  - If you don't use all the memory allocated, you're wasting it
  - If you don't allocate enough, oops.
- **Time to put an element in the array:**
  -
- **Time to get an element from the array:**
  -

**LinkedList**

- Nodes can be non-contiguous
- You can keep growing the list, taking as much memory as you need but not more than you need
- **Time to put a node into the list:**
  -
- **Time to get a node/data from the list**
  -

**hmmmm, how do we calculate this?**

# Summary

**Stack**

- Primary Operations
  - Push
  - Pop
  - Peek
- Helper Operations
  - Create
  - Destroy
  - IsEmpty
  - IsFull

**Linked List**

- Primary Operations
  - Add
  - Remove
- Helper Operations
  - Create
  - Destroy
  - IsEmpty
  - Contains(Node), Contains(Data)
  - InsertBefore(), InsertAfter()
  - AddAtHead(), AddAtTail()

# Summary

**Stack**

- The abstraction is more important than the implementation
  - We implemented as an array; could also use a list.

**Linked List: Alternative to Array**

- Could be single or double
  - We talked about single
  - We implemented double
  - Code for single is in Github
- The List is really just a pointer to a single node
  - We implemented a wrapper struct that helped us keep track of the head
  - We can add metadata to that struct to help
    - Such as NumItems, ptr to LastNode.

# Next time:

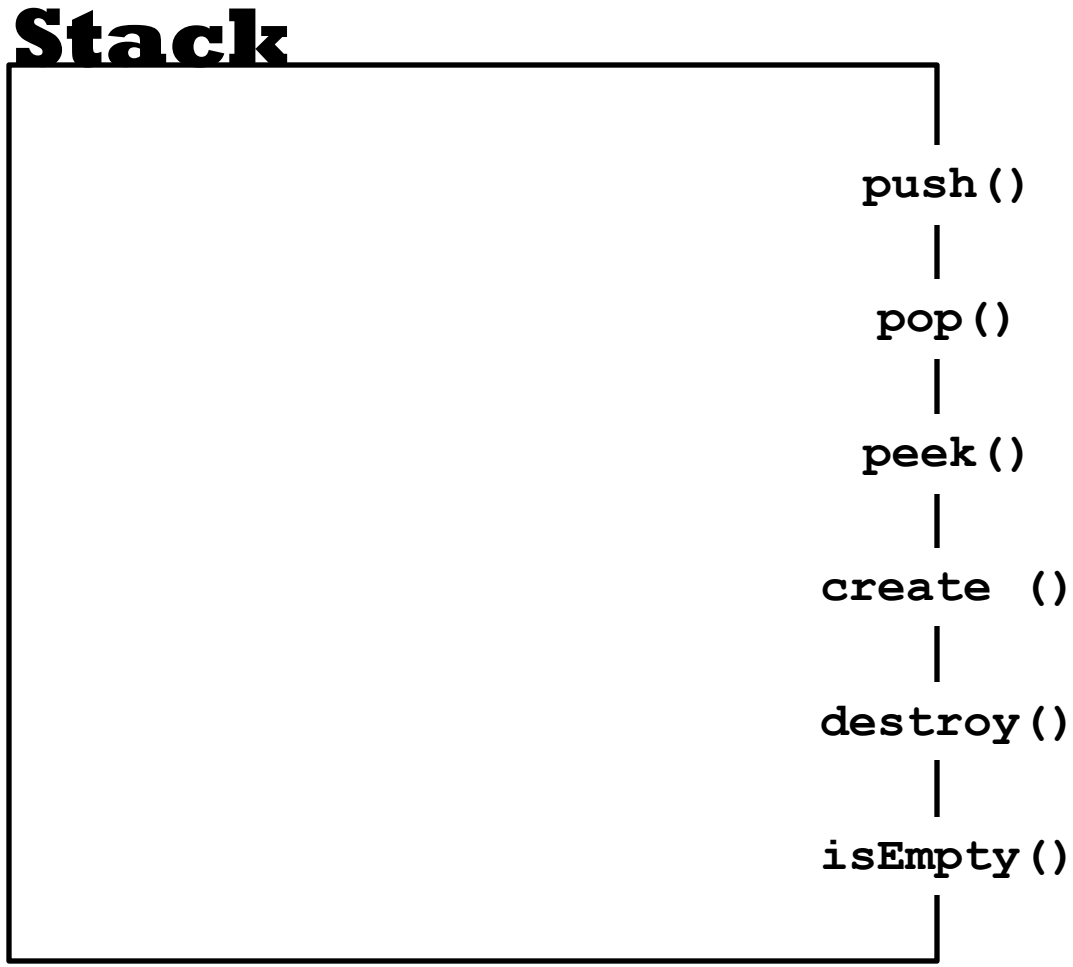
- Finish up with Linked Lists
- Queues
- Big O complexity and performance
  - How to talk about our algorithms.

# ABSTRACT DATA TYPES

# Abstract Data Types

- It's about the interface
- The concrete implementation can vary

# A stack is a black box, with a well-defined interface:



# The implementation (code) is independent of the operations.

## Stack

```
stackOfBooks* create(){
    // Allocate space on the heap
    stackOfBooks* newStack =
        (stackOfBooks*)malloc(sizeof(stackOfBooks));
    // Initialize anything
    newStack->bookAtTop = -1;

    // For purposes of demo, I'm doing this here. It's not always necessary:
    int i=0;
    for (i=0; i<MAXSIZE; i++){
        newStack->booknames[i] = "";
    }

    // Return pointer to new stack
    return newStack;
}


void destroy(stackOfBooks* bookStack){
    // Free anything that hasn't been freed

    // Free the stack
    free(bookStack);
}


stackOfBooks* push(char* newBook, stackOfBooks* bookStack){
    // Update the head index
    bookStack->bookAtTop++;

    // Put the element in the array
    bookStack->booknames[bookStack->bookAtTop] = newBook;

    return bookStack;
}


char* pop(stackOfBooks* bookStack){
    // Get the element from the array
    return bookStack->booknames[bookStack->bookAtTop--];

    // Update the head index???
}


char* peek(stackOfBooks* bookStack){
    // Get the element from the array
    return bookStack->booknames[bookStack->bookAtTop];
```

push()

pop()

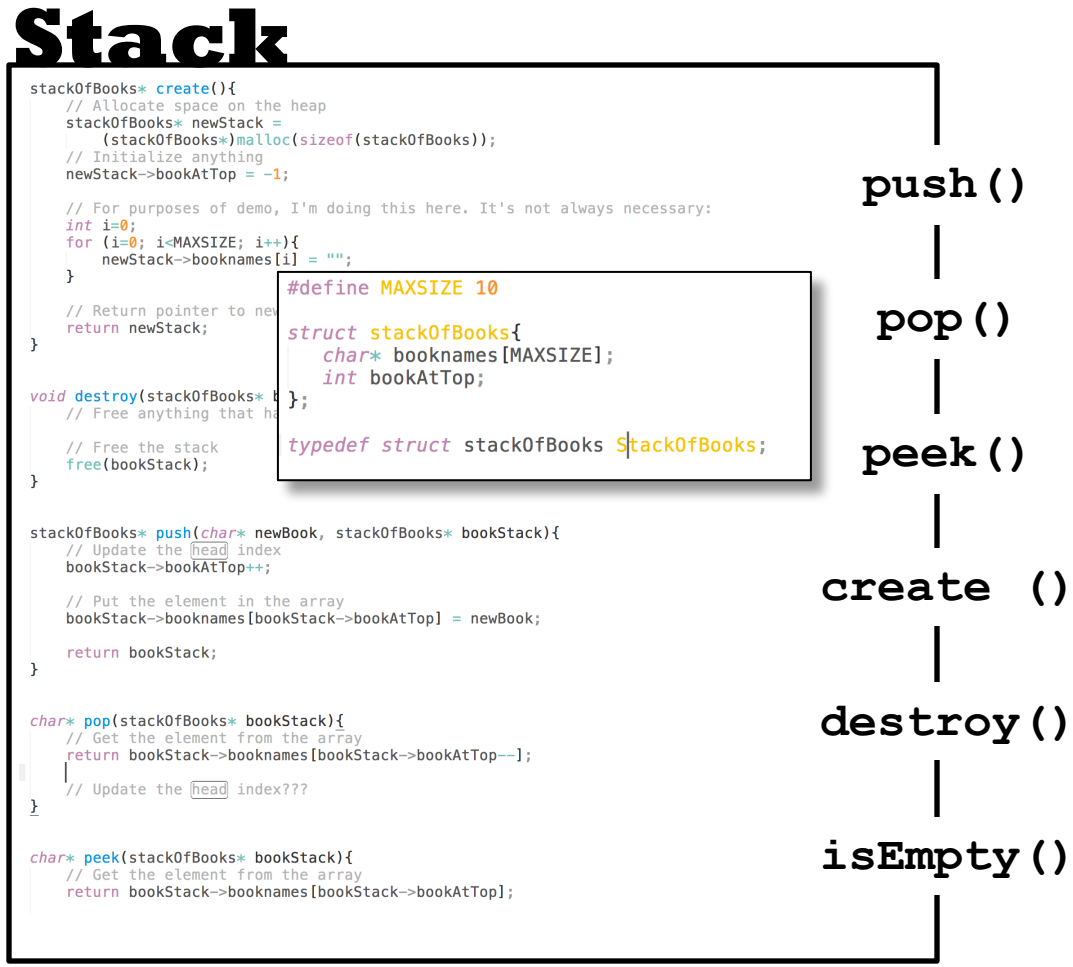
peek()

create ()

destroy()

isEmpty()

# Stack can be implemented with an array…



# …or with a LinkedList.

## Stack

```
stackOfBooks* create(){
    // Allocate space on the heap
    stackOfBooks* newStack =
        (stackOfBooks*)malloc(sizeof(stackOfBooks));
    // Initialize anything
    newStack->bookAtTop = -1;

    // For purposes of demo, I'm doing this here. It's not always necessary:
    int i=0;
    for (i=0; i<MAXSIZE; i++){
        newStack->booknames[i] = "";
    }

    // Retu
    return
}

void destro
    // Free

    // Free
    free(bookStack);
}

stackOfBooks* push(char* newBook, stackOfBooks* bookStack){
    // Update the head index
    bookStack->bookAtTop++;

    // Put the element in the array
    bookStack->booknames[bookStack->bookAtTop] = newBook;

    return bookStack;
}

char* pop(stackOfBooks* bookStack){
    // Get the element from the array
    return bookStack->booknames[bookStack->bookAtTop--];

    // Update the head index???
}

char* peek(stackOfBooks* bookStack){
    // Get the element from the array
    return bookStack->booknames[bookStack->bookAtTop];
```

```
struct stackOfBooks{
    BookNode headOfList;
}

typedef struct stackOfBooks StackOfBooks;
```

push()

pop()

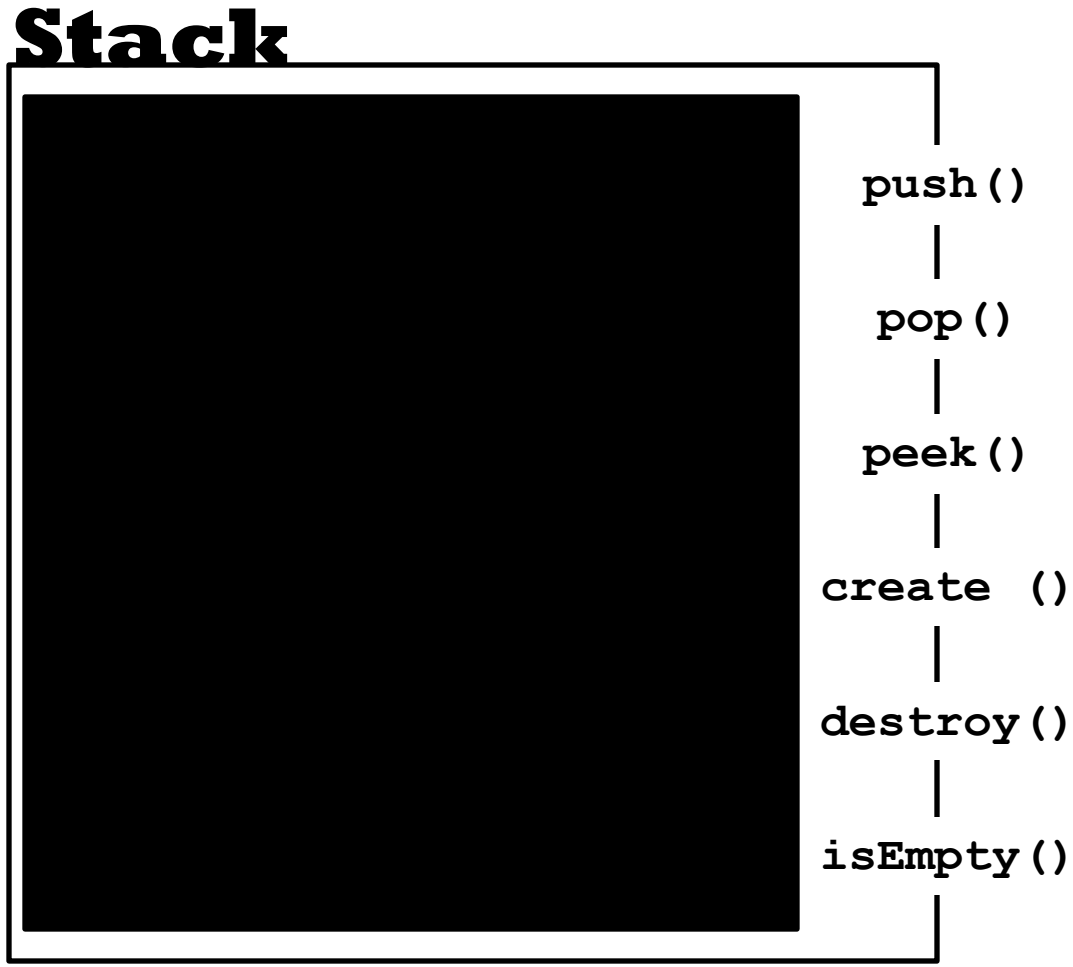
peek()

create ()

destroy()

isEmpty()

# But even as the code changes, we know the operations will stay the same.

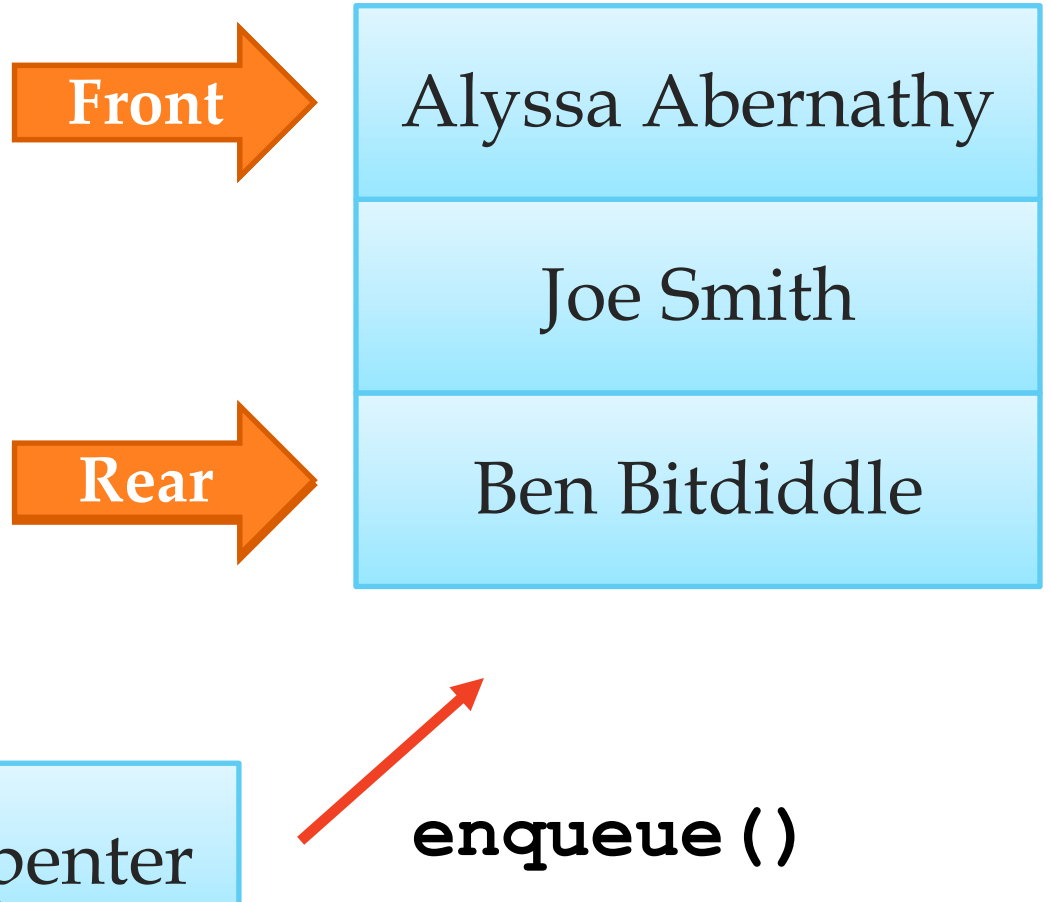


- Abstract Data Types (ADTs) define the operations or interface of a data structure
- The opposite of an ADT is a Concrete Data Type (CDT)
- ADTs demonstrate how defining the interface allows us to decouple the implementation

# QUEUES

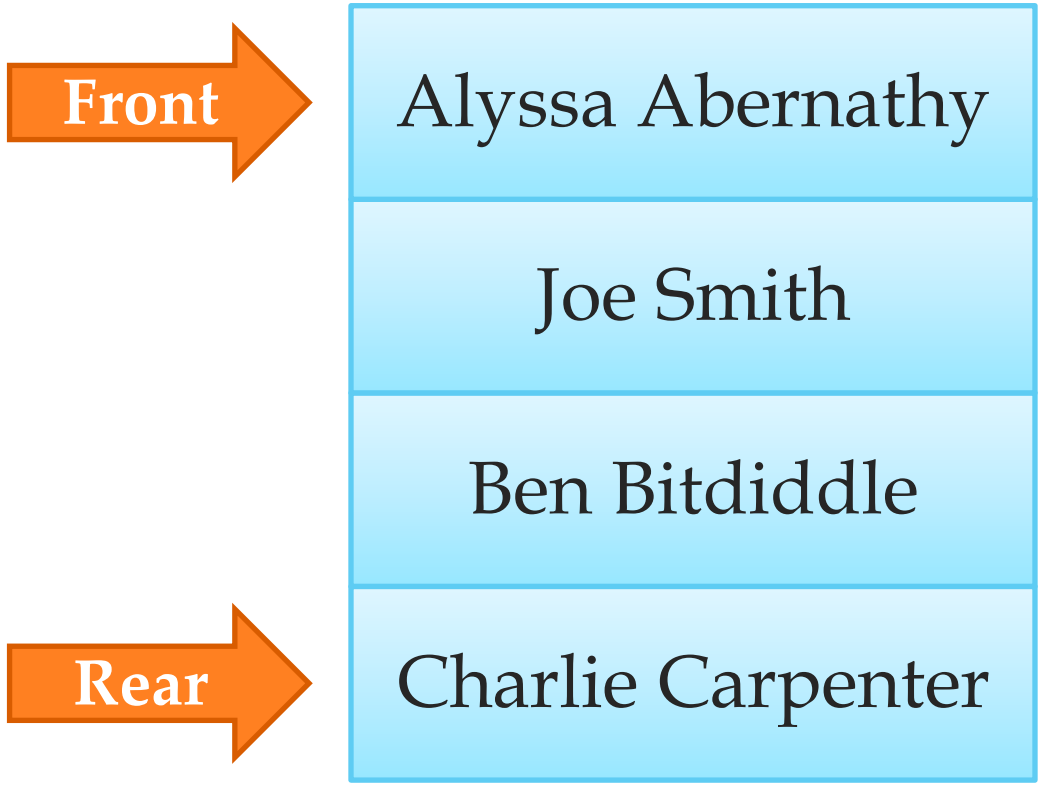
A ***Queue*** allows us to process elements in the order they arrive.

# What is a queue?



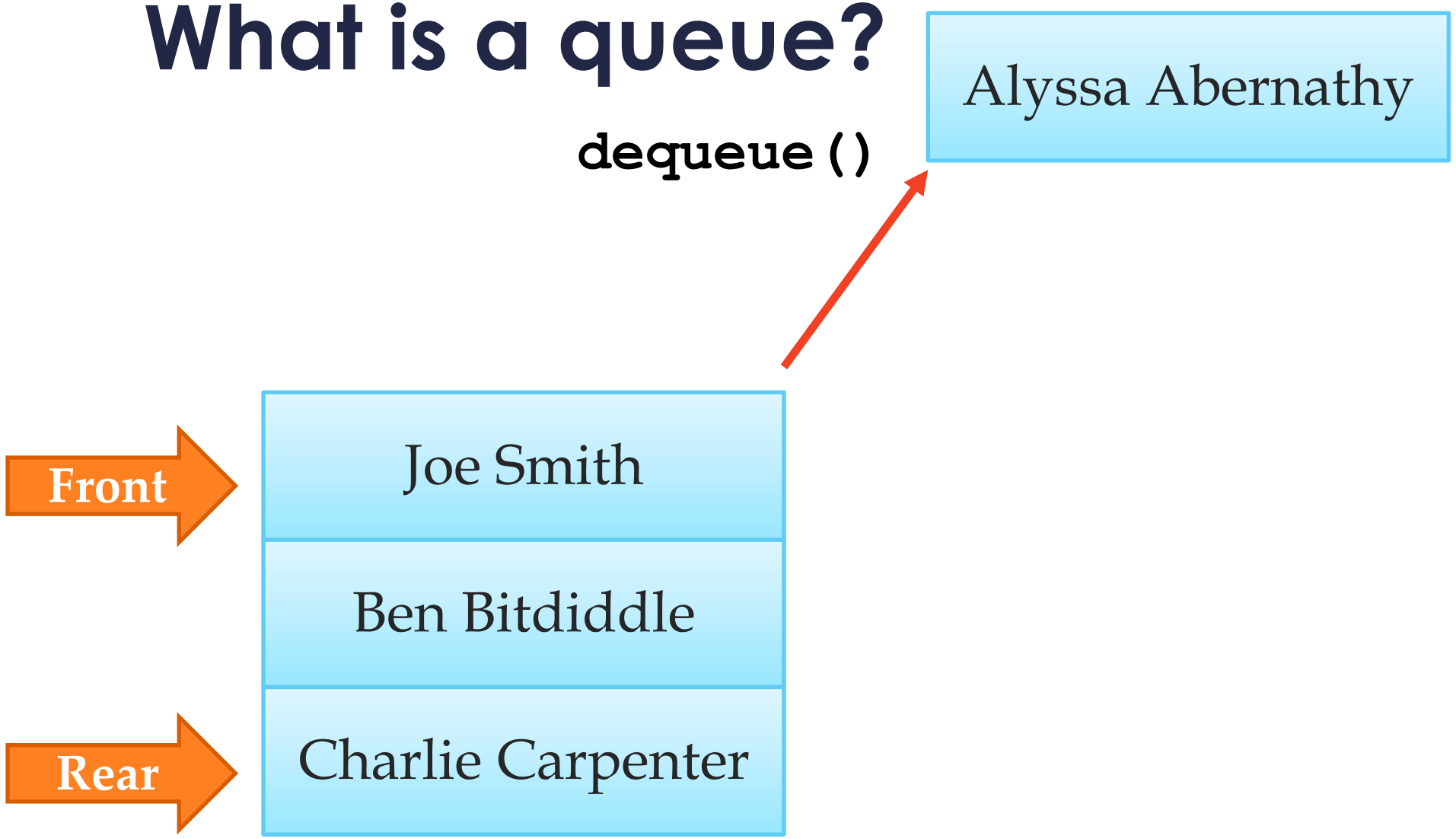
# What is a queue?

`dequeue()`



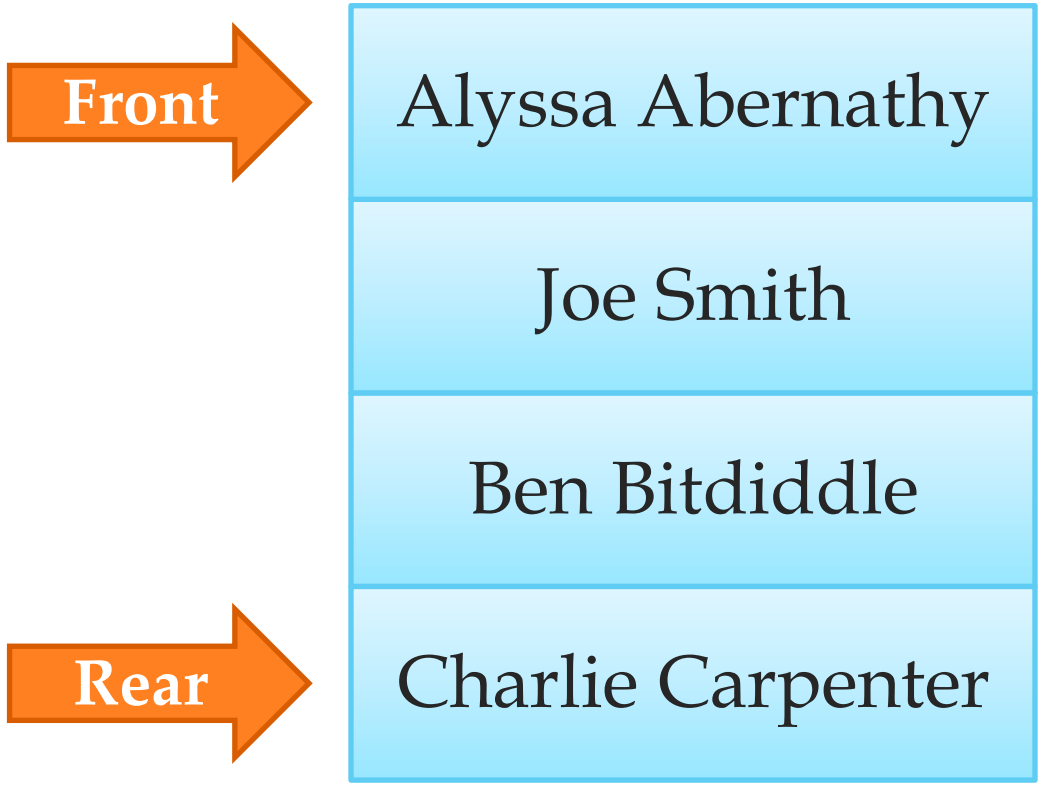
# What is a queue?

`dequeue()`

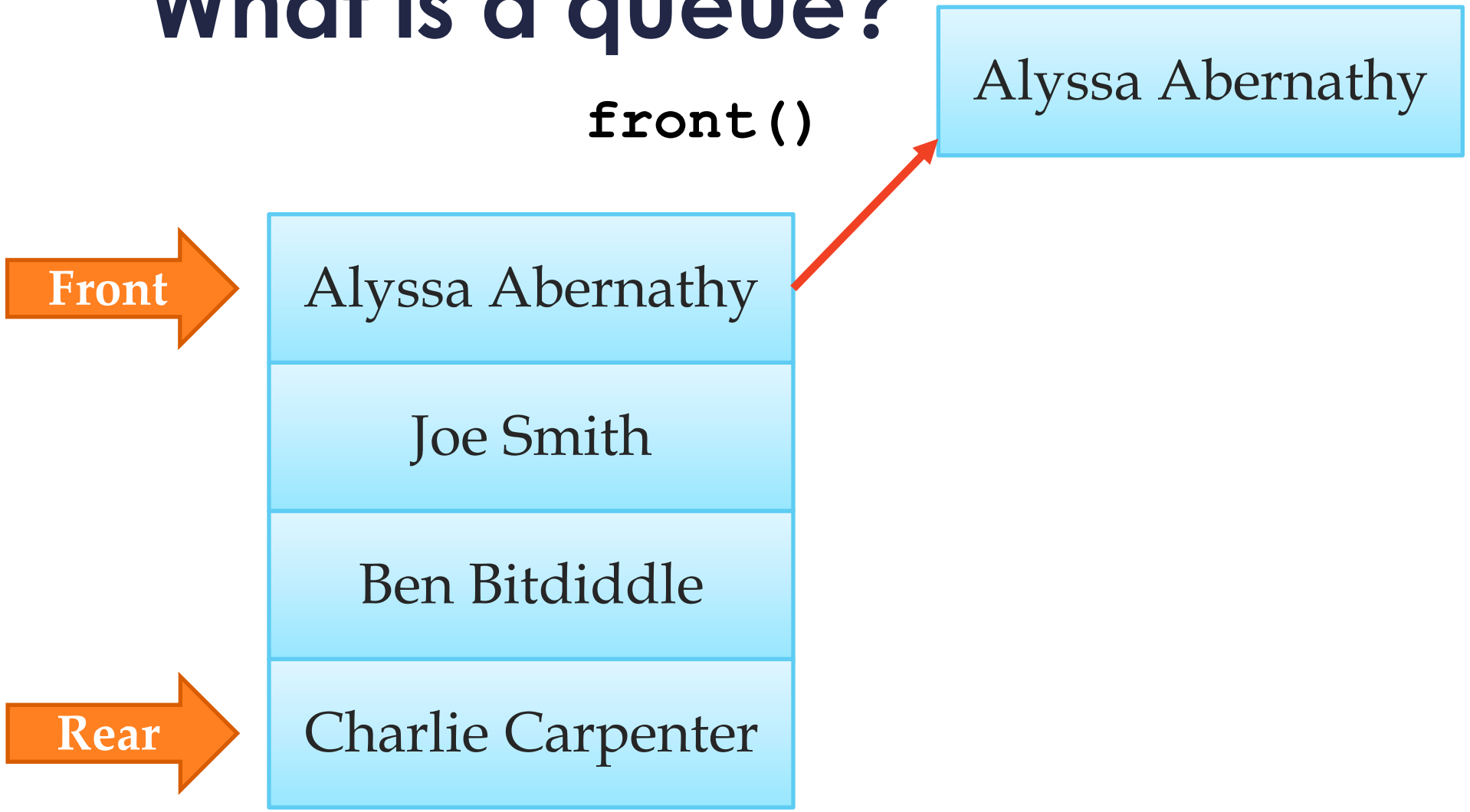


# What is a queue?

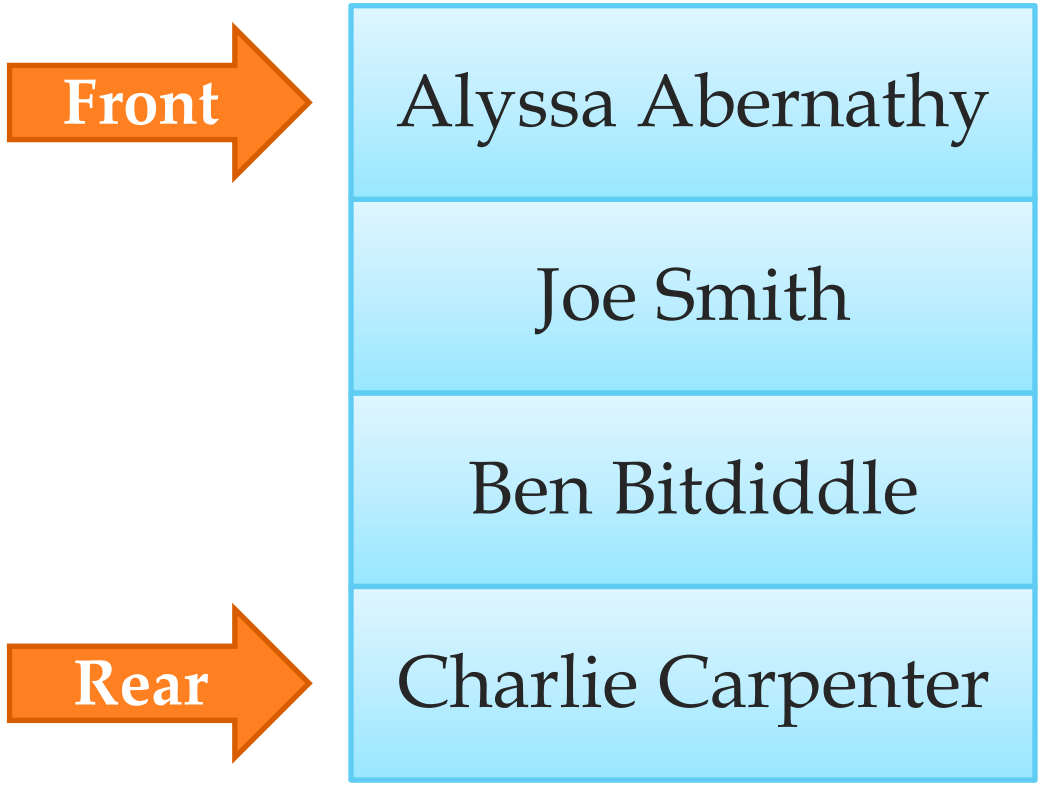
`front()`



# What is a queue?

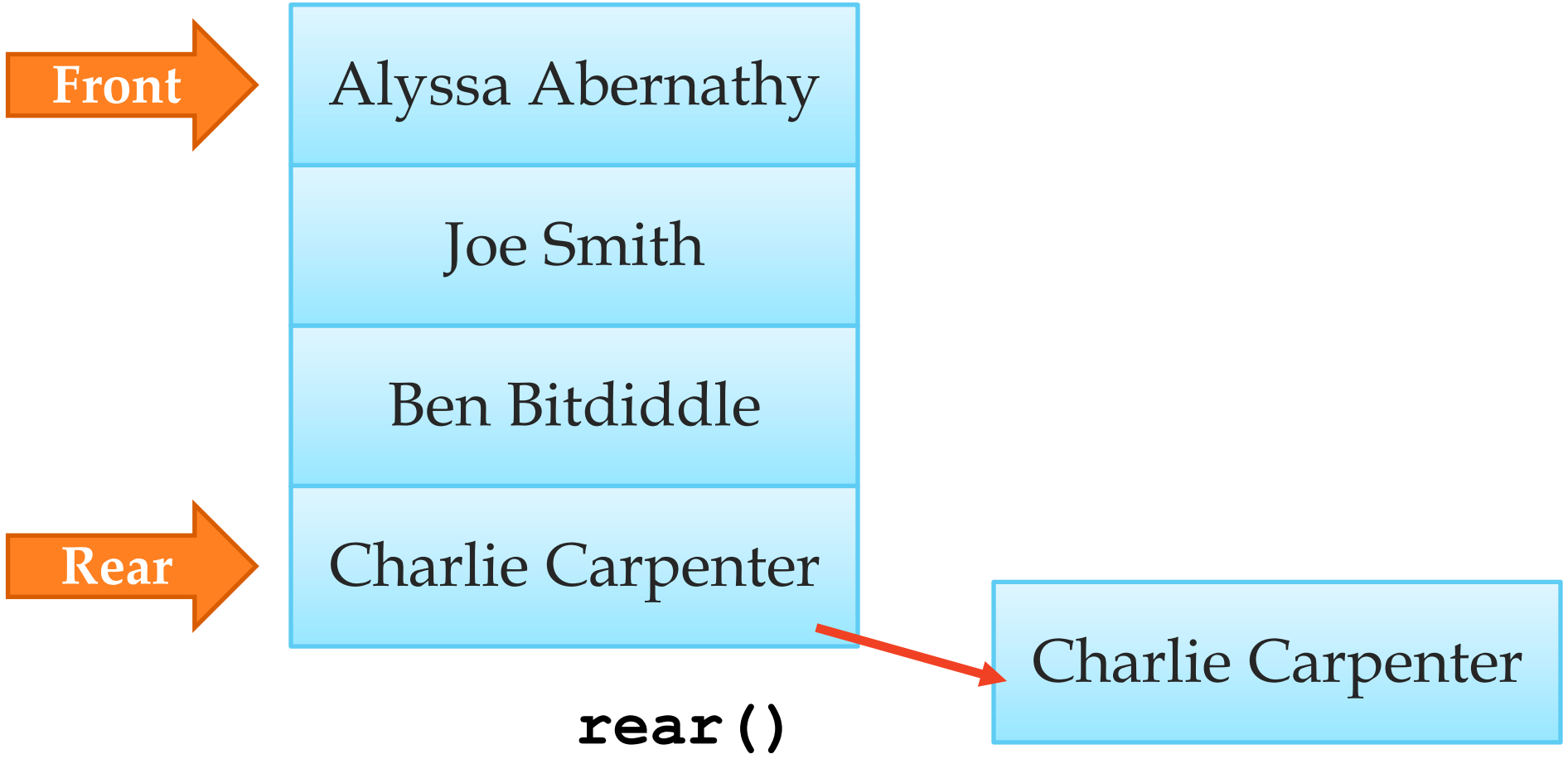


# What is a queue?



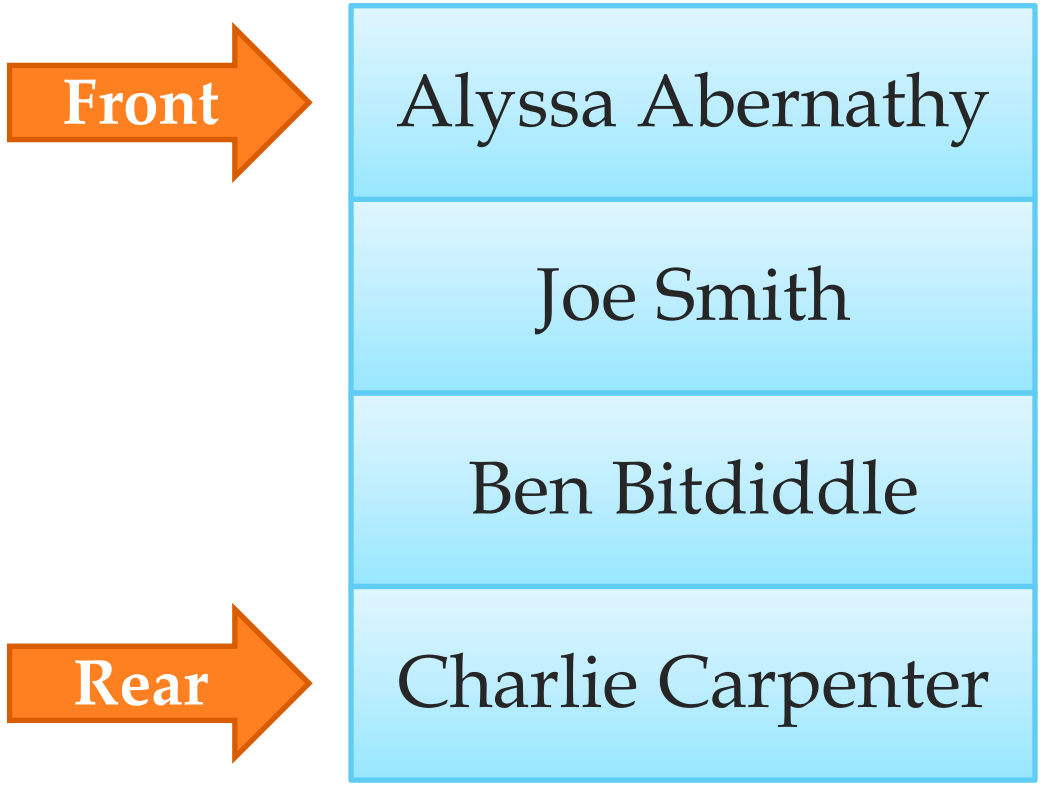

`rear()`

# What is a queue?



# What is a queue?

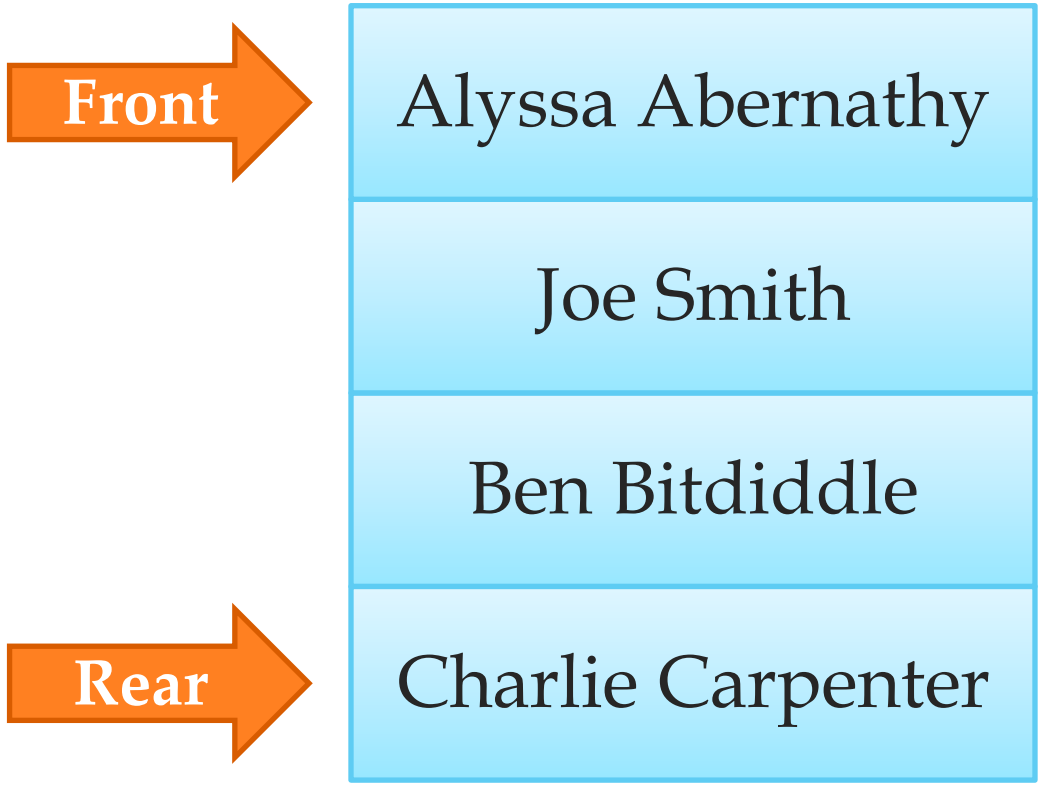
`dequeue()` `front()`




`enqueue()` `rear()`

# What is a queue?

`dequeue()` `front()`



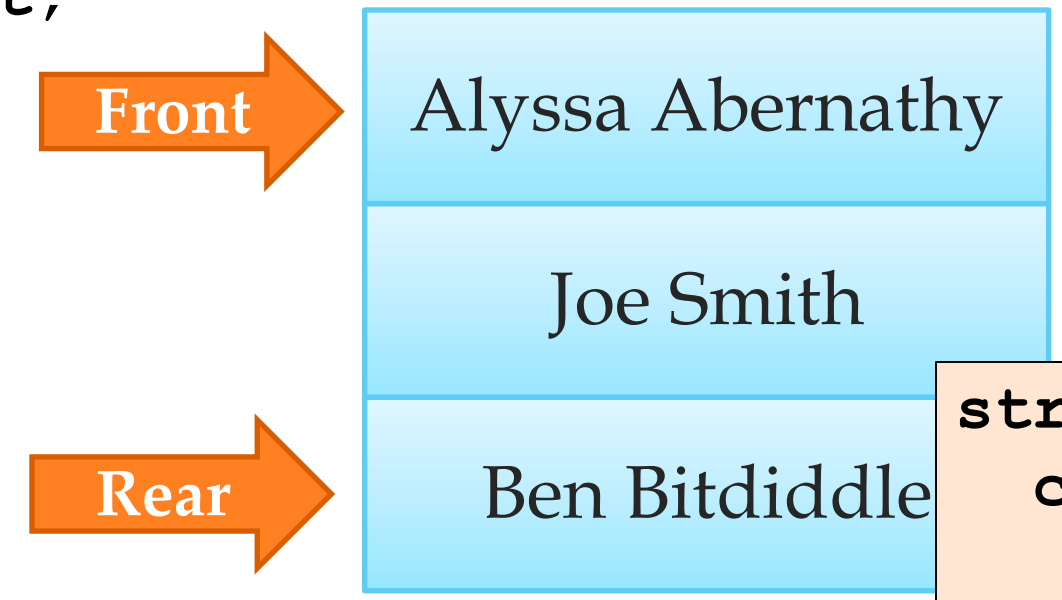

**FIFO:**
**First In,**
**First Out**

`enqueue()` `rear()`

# What is a queue in C?

# What is a queue in C?

```
int front;
```




```
char* customers[];
```

```
int rear;
```

```
struct queueOfCustomers{
   char* customers[SIZE];
    int front;
    int rear;
};
```

# Building a Queue with an array

How many elements does the queue have?

```
size = rear - front;
```

# Enqueue: Adding elements

**What changes with our pointers when we add an element?**

**Policy v1:**
**Rear** always points at the next open slot.
**Front** always points at the next available element.
**Size** = Rear – Front

```
enqueue("Ben Bitdiddle");
```

# Enqueue: Adding elements

What changes with our pointers when we add an element?

**Policy v1:**
**Rear** always points at the next open slot.
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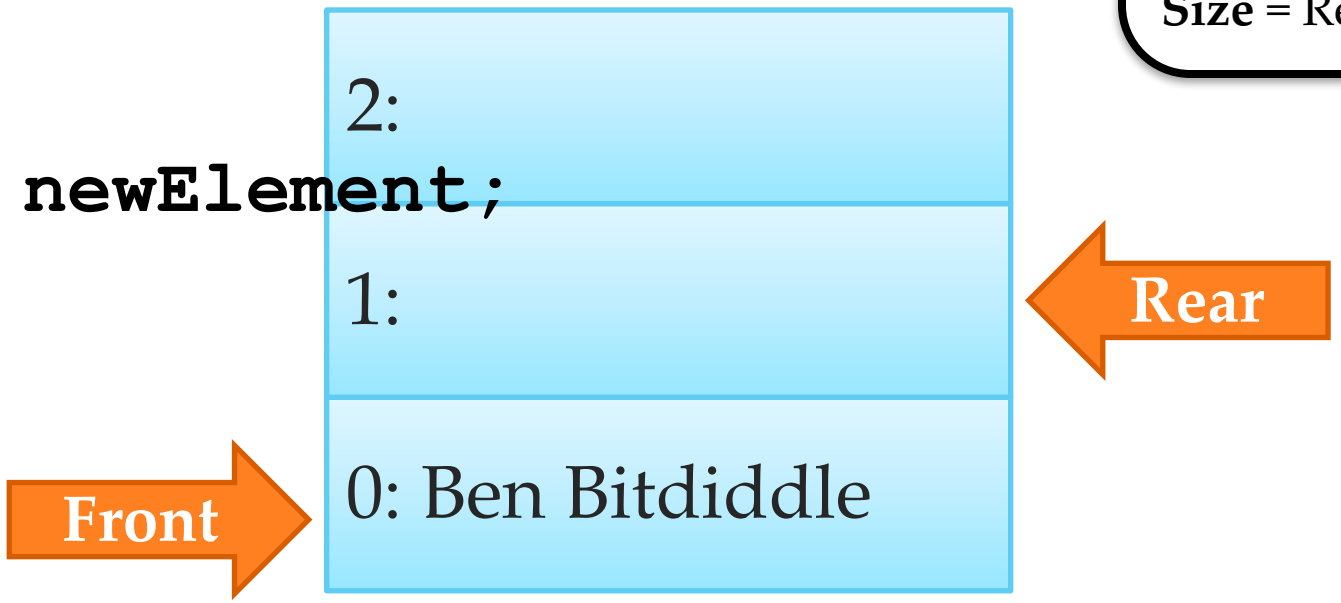
```
enqueue("Ben Bitdiddle");
```

```
array[rear] = newElement;
rear++;
```



# Enqueue: Adding elements

**What changes with our pointers when we add an element?**

```
enqueue("Joe Smith");
```

```
array[rear] = newElement;
rear++;
```


**Policy v1:**
**Rear** always points at the next open slot.
**Front** always points at the next available element.
**Size** = Rear – Front

# Enqueue: Adding elements

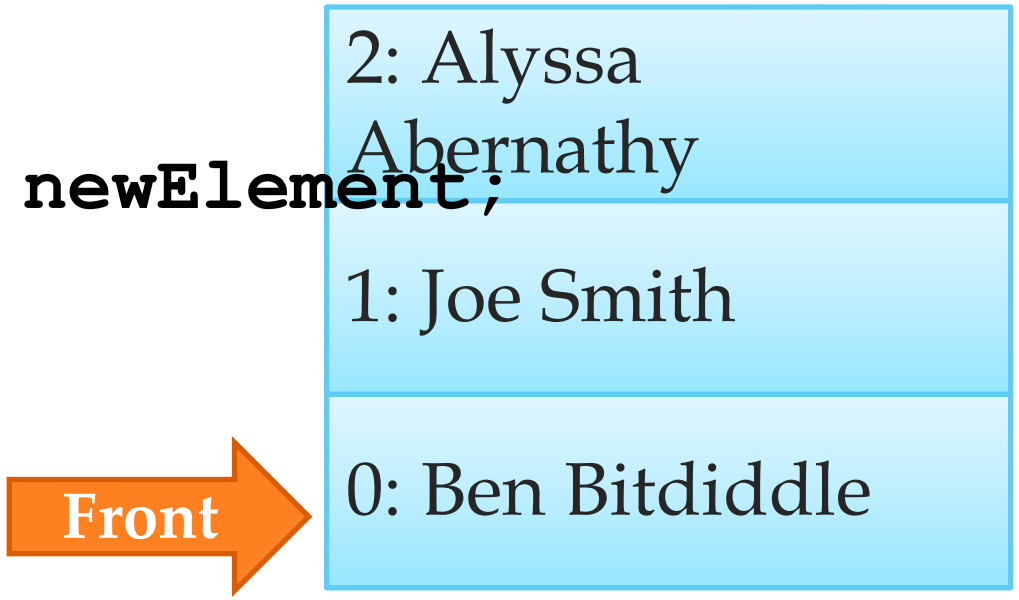
What changes with our pointers when we add an element?

!!!

Rear

```
enqueue("Alyssa Abernathy");
```

```
array[rear] = newElement;
rear++;
```

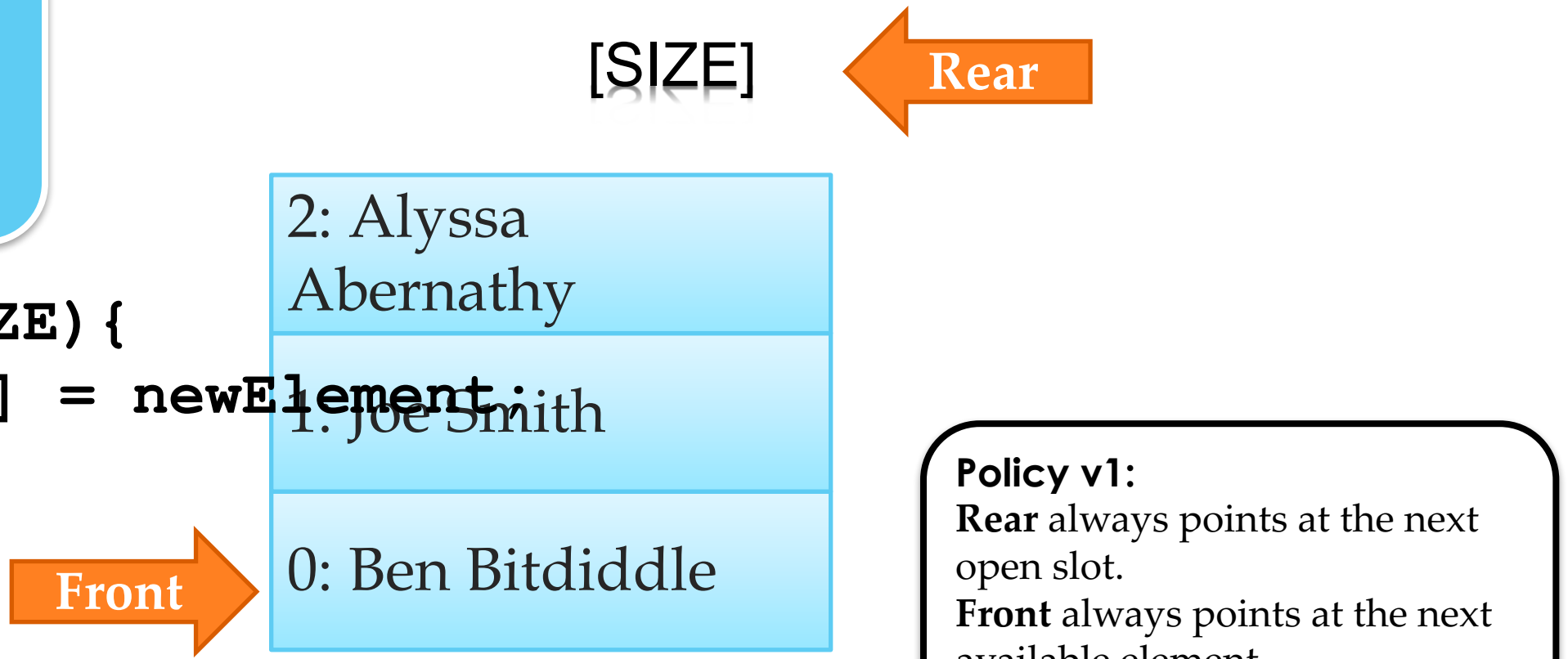



**Policy v1:**
**Rear** always points at the next open slot.
**Front** always points at the next available element.
**Size** = Rear – Front

# Enqueue: Adding elements

Add a guard to `enqueue()`, so we don't insert an element into a non-existent slot:

```
if (rear < SIZE){
    array[rear] = newElement;
    rear++;
}
```




**Policy v1:**
**Rear** always points at the next open slot.
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# Dequeue: Removing elements

**What changes with our pointers when we REMOVE an element?**

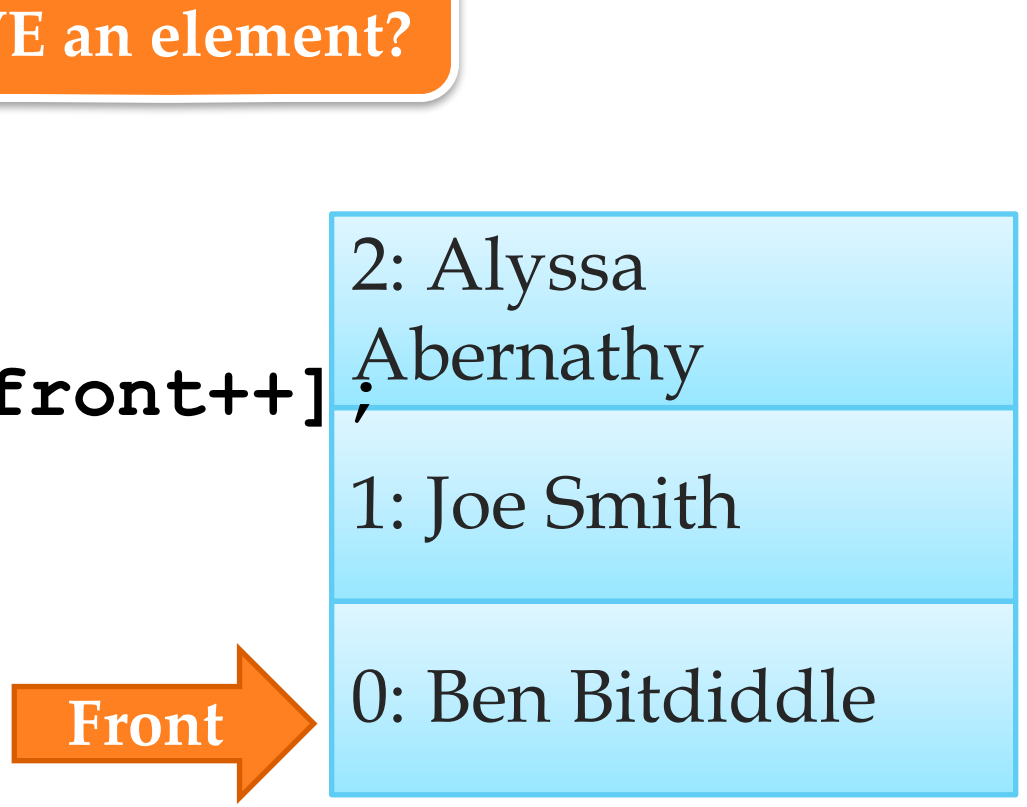

**Policy v1:**
**Rear** always points at the next open slot.
**Front** always points at the next available element.
**Size** = Rear – Front

# Dequeue: Removing elements

**What changes with our pointers when we REMOVE an element?**

```
dequeue();

return array[front++];
```

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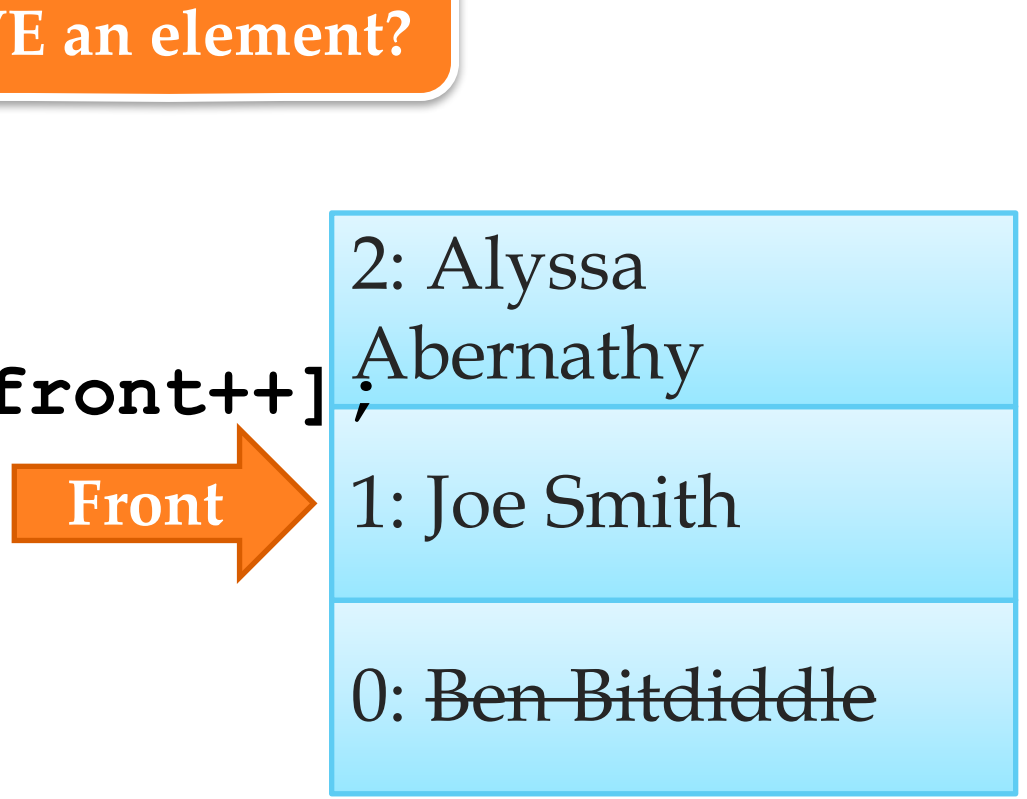
# Dequeue: Removing elements

What changes with our pointers when we REMOVE an element?

```
dequeue();

return array[front++];
```

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# Dequeue: Removing elements

What changes with our pointers when we REMOVE an element?

```
dequeue();

return array[front++];
```


**Policy v1:**
**Rear** always points at the next open slot.
**Front** always points at the next available element.
**Size** = Rear – Front

# Dequeue: Removing elements

What changes with our pointers when we REMOVE an element?

```
dequeue();

return array[front++];
```

Front

Rear


**Policy v1:**
**Rear** always points at the next open slot.
**Front** always points at the next available element.
**Size** = Rear – Front

# Dequeue: Removing elements

What changes with our pointers when we REMOVE an element?

```
dequeue();

return array[front++];
```

Front

Rear

2: ~~Alyssa Abernathy~~

1: ~~Joe Smith~~

0: ~~Ben Bitdiddle~~

Also, add a guard to dequeue(), so we don't try to access an empty slot.

- if queue isEmpty()?
- if front == SIZE?

Coming back …

**Policy v1:**
**Rear** always points at the next open slot.
**Front** always points at the next available element.
**Size** = Rear – Front

# Dequeue: Removing elements

What changes with our pointers when we REMOVE an element?

Front

Rear

2: Alyssa

Aaliyah

```
return array[front++];
```

1: Joe Smith

0: ~~Ben Bitdiddle~~

**Now What?**

**Can we reset our queue?**

**Policy v1:**
**Rear** always points at the next open slot.
**Front** always points at the next available element.
**Size** = Rear – Front

# Can we re-use empty slots?


**Policy v1:**
**Rear** always points at the next open slot.
**Front** always points at the next available element.
**Size** = Rear – Front

# Can we re-use empty slots?

**Policy v1:**
**Rear** always points at the next open slot.
**Front** always points at the next available element.
~~**Size** = Rear – Front~~


```
// Update Enqueue to point
// the rear at zero to reuse
// now-empty slots
    array[rear] = newElement;
    rear++;
if (rear >= SIZE){
    rear = 0;
}
```

# Re-using empty slots: tracking size

**Policy v2:**
**Rear:** always points at the next open slot.
**Front:** always points at the next available element.
**Size:** keep track of separately.


```
// Update Enqueue to point
// the rear at zero to reuse
// now-empty slots
    array[rear] = newElement;
    rear++;
if (rear >= SIZE){
    rear = 0;
}
```

# Re-using empty slots: tracking size

**Policy v2:**
**Rear:** always points at the next open slot.
**Front:** always points at the next available element.
**Size:** keep track of separately.


```
// Update Enqueue to point
// the rear at zero to reuse
// now-empty slots
    array[rear] = newElement;
    rear++;
if (rear >= SIZE){
    rear = 0;
}
```

```
struct queueOfCustomers{
    char* customers[SIZE];
    int front;
    int rear;
    int size;
};
```

# Hmmm… what's happening here?

**Policy v2:**
**Rear:** always points at the next open slot.
**Front:** always points at the next available element.
**Size:** keep track of separately.

```
enqueue("Harry Potter");
```

# Updating the policy again:

**Policy v3:**
**Rear:** always points at the next open slot.
**Front:** always points at the next available element.
**Size:** keep track of separately.
If queue is **full**, can't enqueue.
If queue is **empty**, can't dequeue.


```
// Update Enqueue to check for full
if (rear == front){
    // QUEUE IS FULL!!
    return;
}
if (rear < SIZE){
    array[rear] = newElement;
    rear++;
    size++;
}
if (rear >= SIZE){
    rear = 0;
}
```

…this is getting complicated.

# Can we be smarter about this?

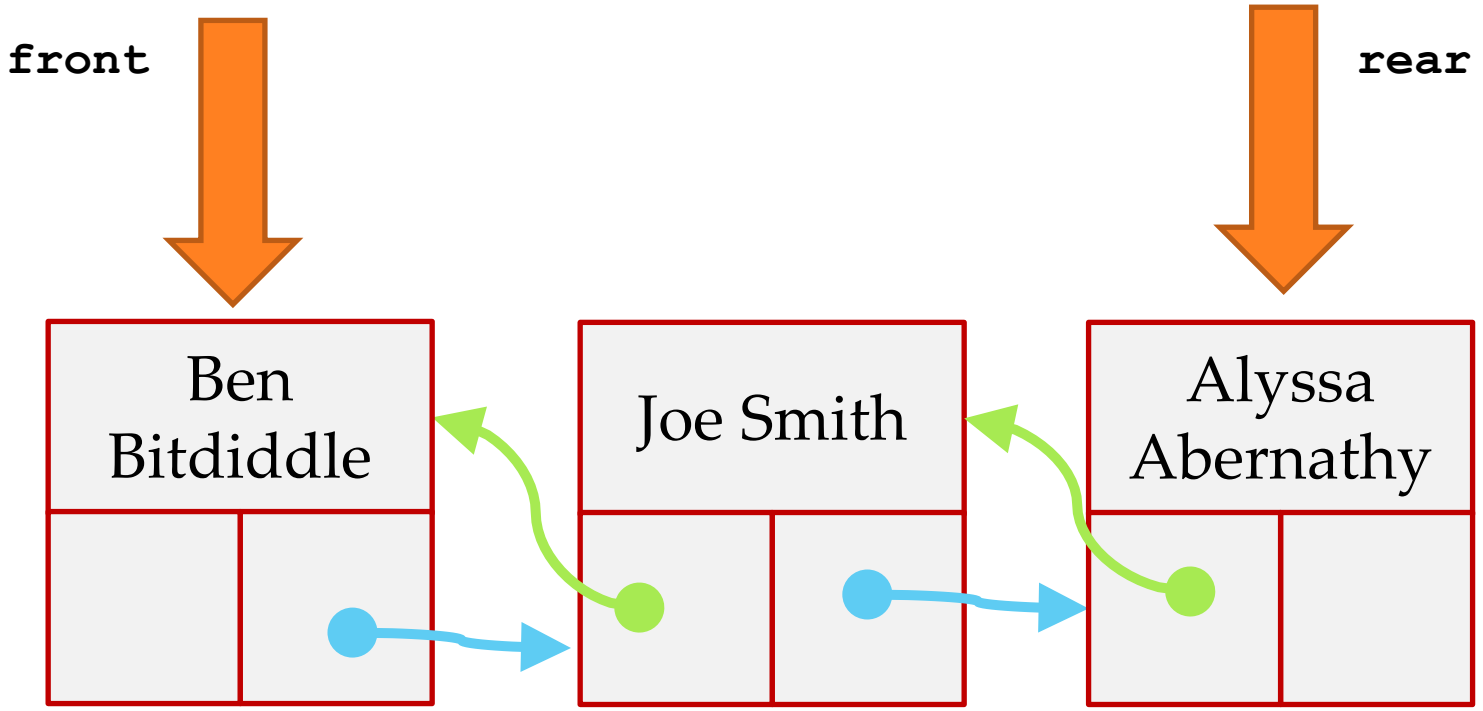
**A queue is an Abstract Data Type. That means we can choose a different implementation if we want!**

**What other data structures can we use?**

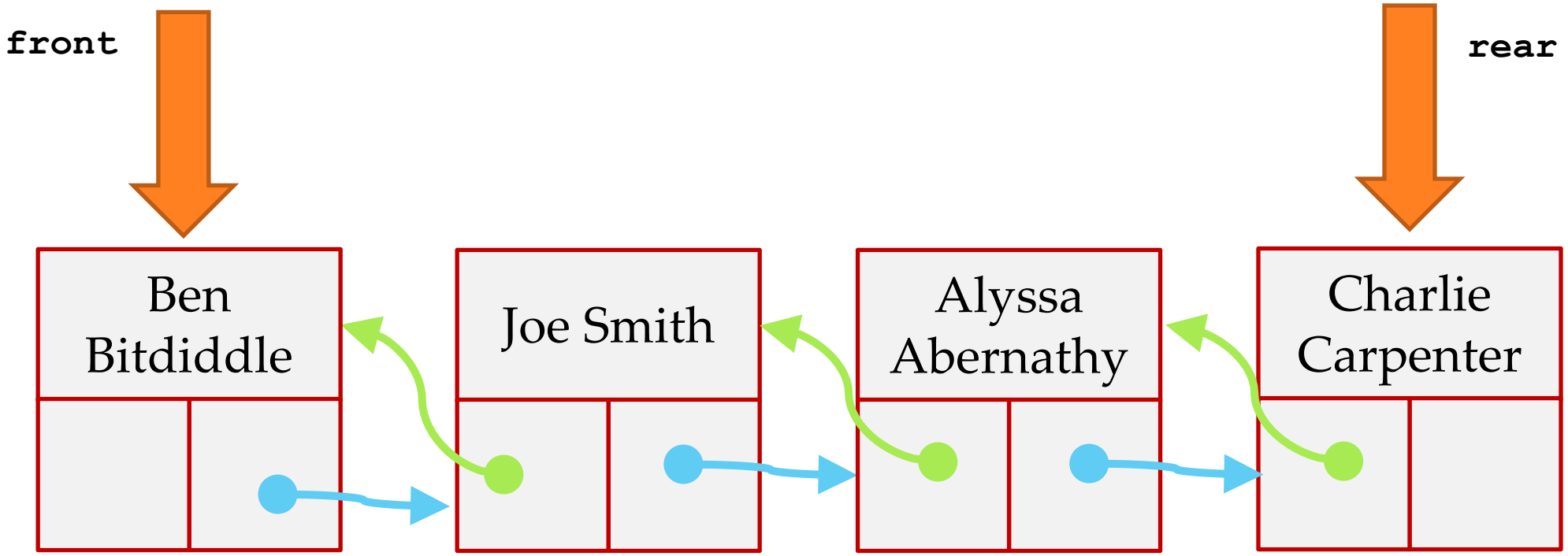
# Linked List?
# Stack?

# Building a Queue with a Linked List

# Building a Queue with Linked List



# Enqueue: Adding an element

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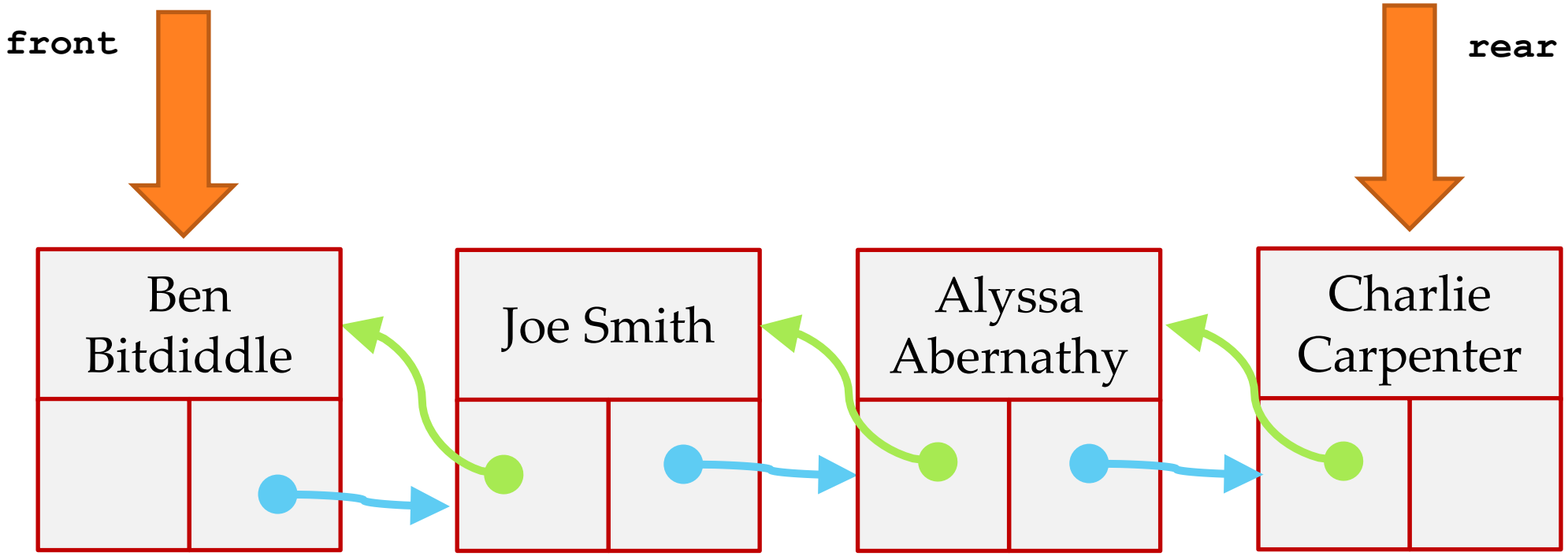


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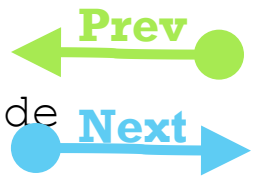

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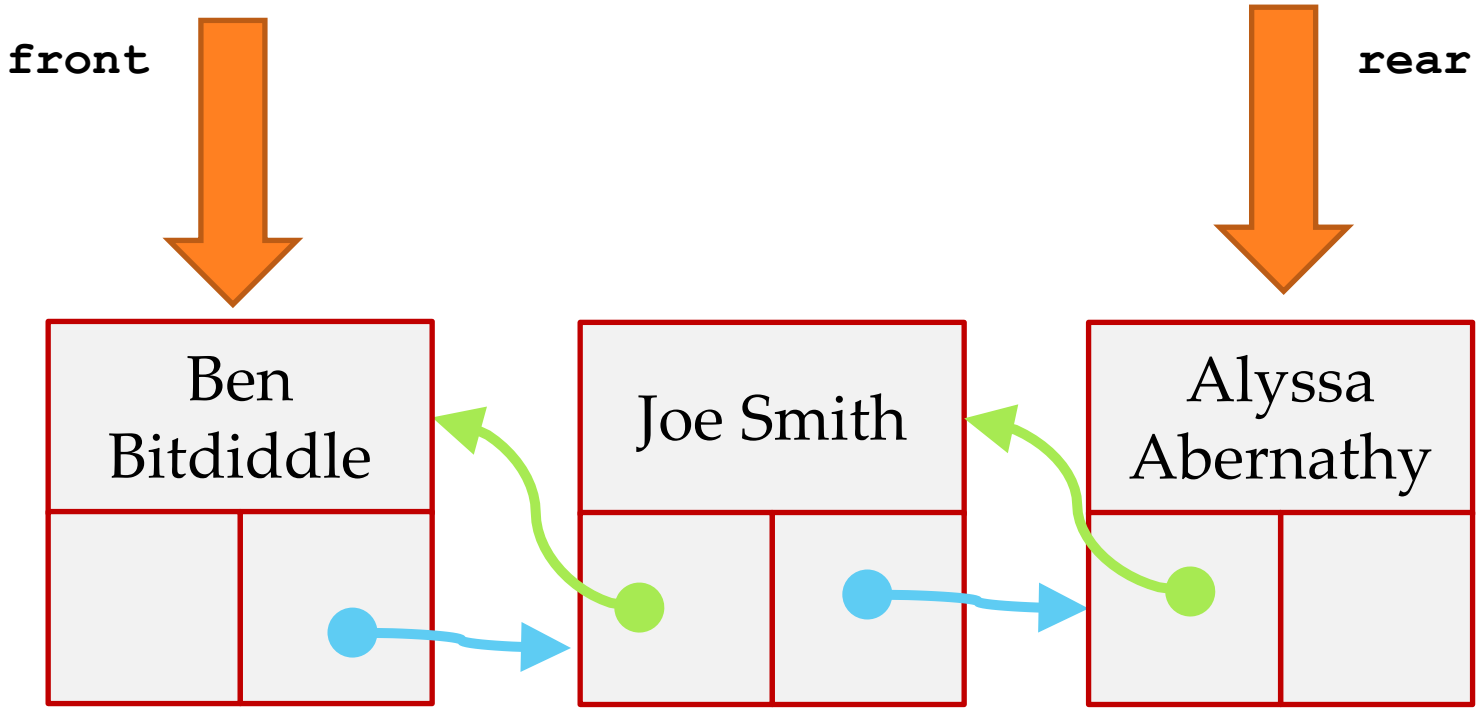


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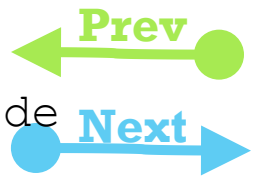

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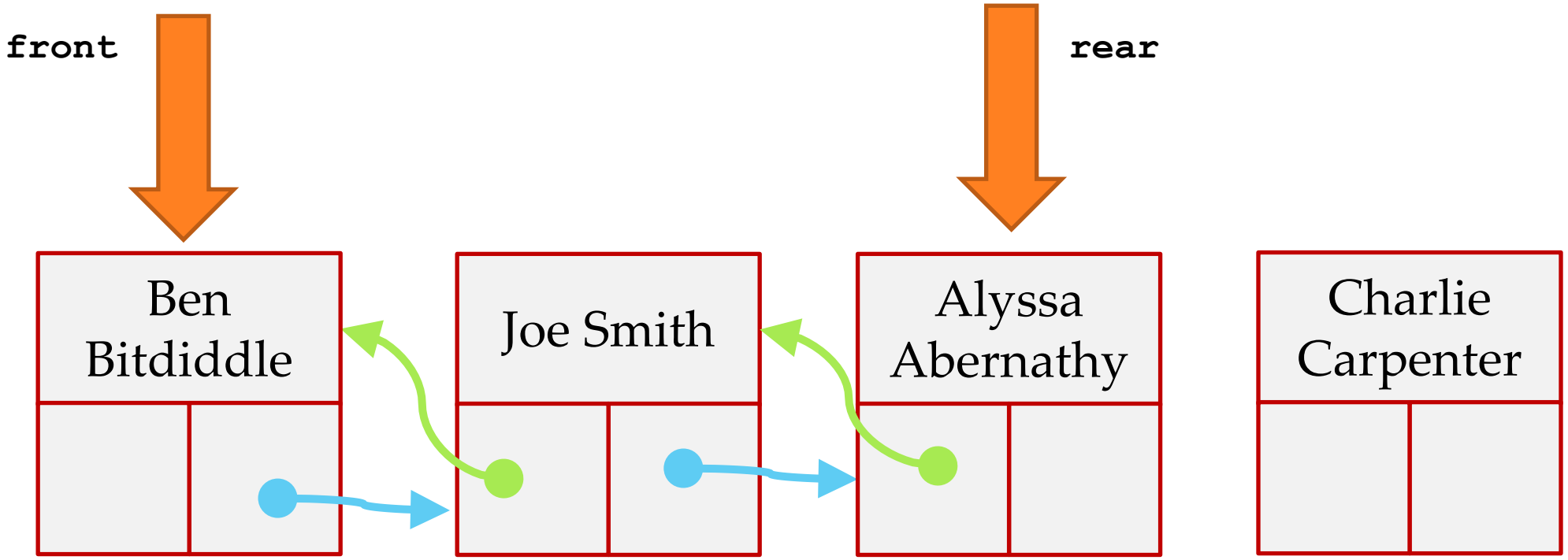


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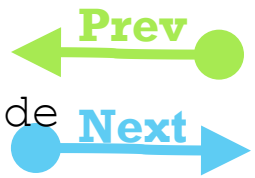

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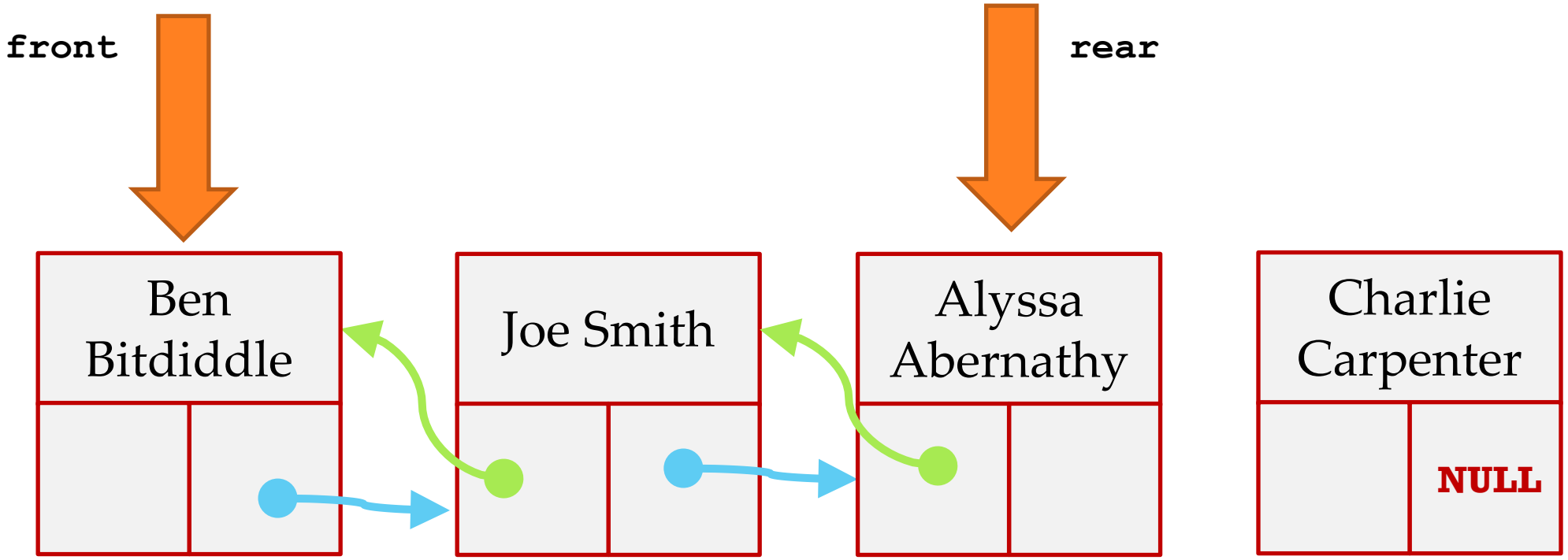


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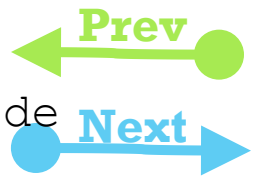

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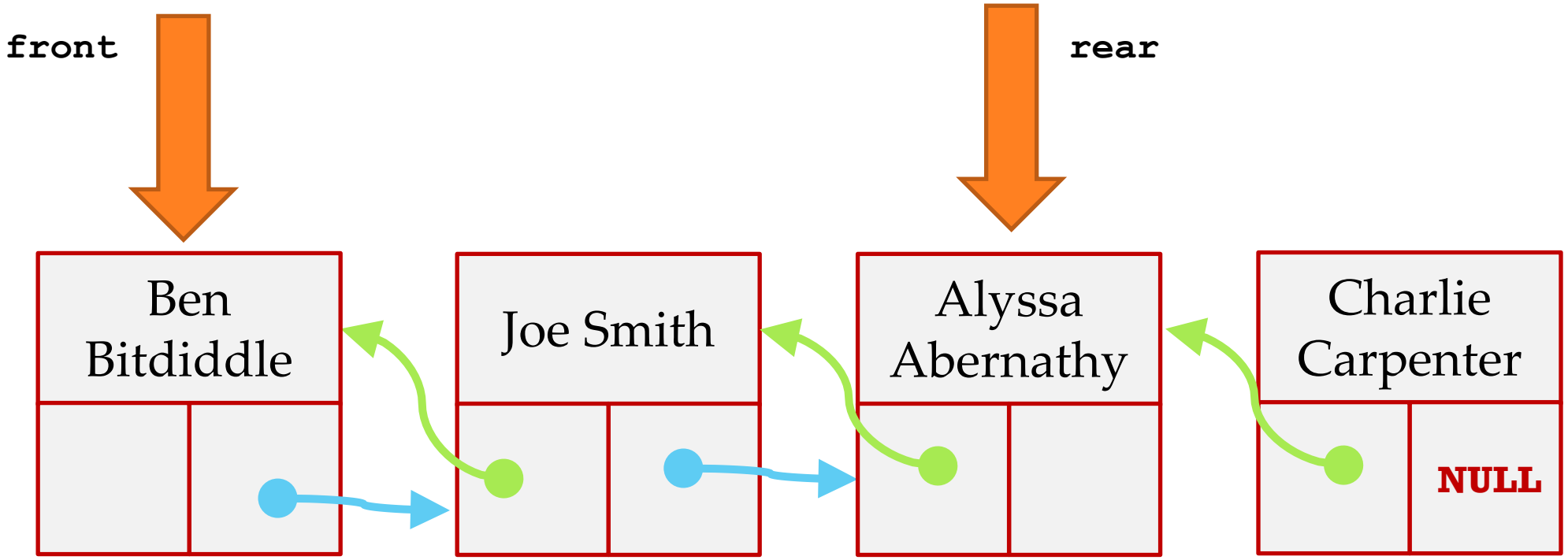


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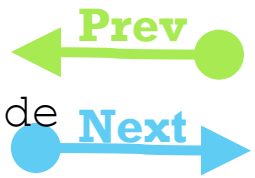

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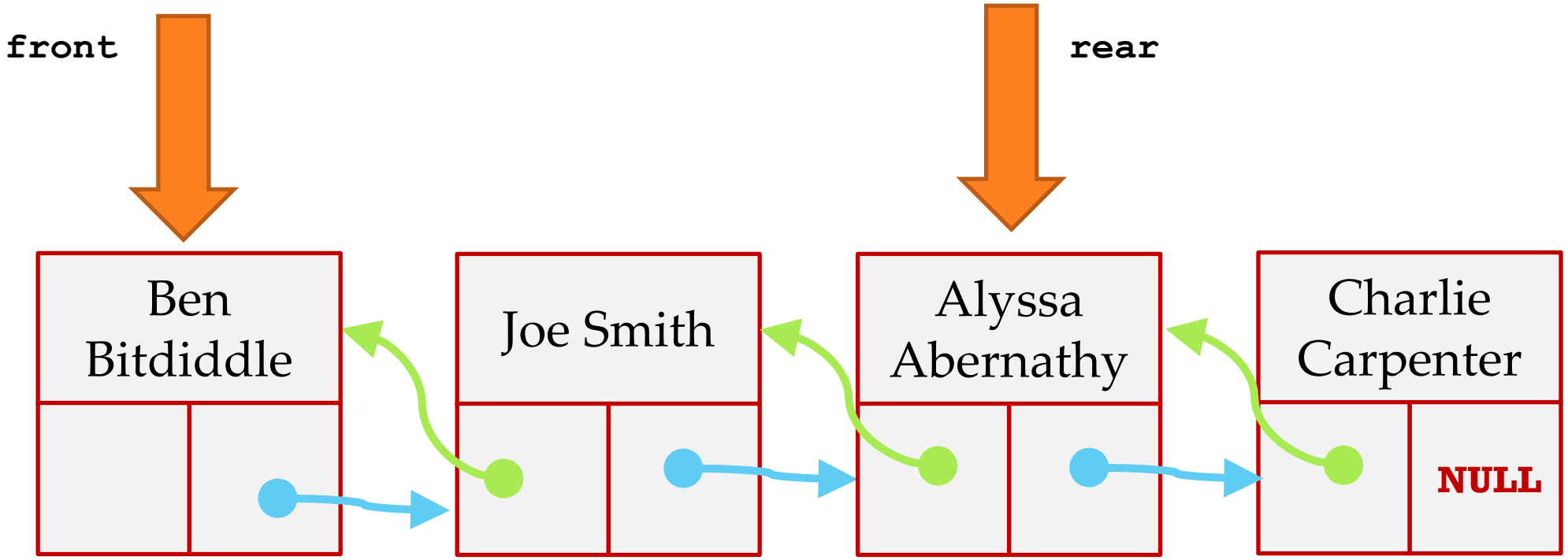


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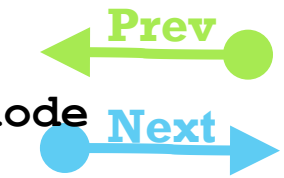

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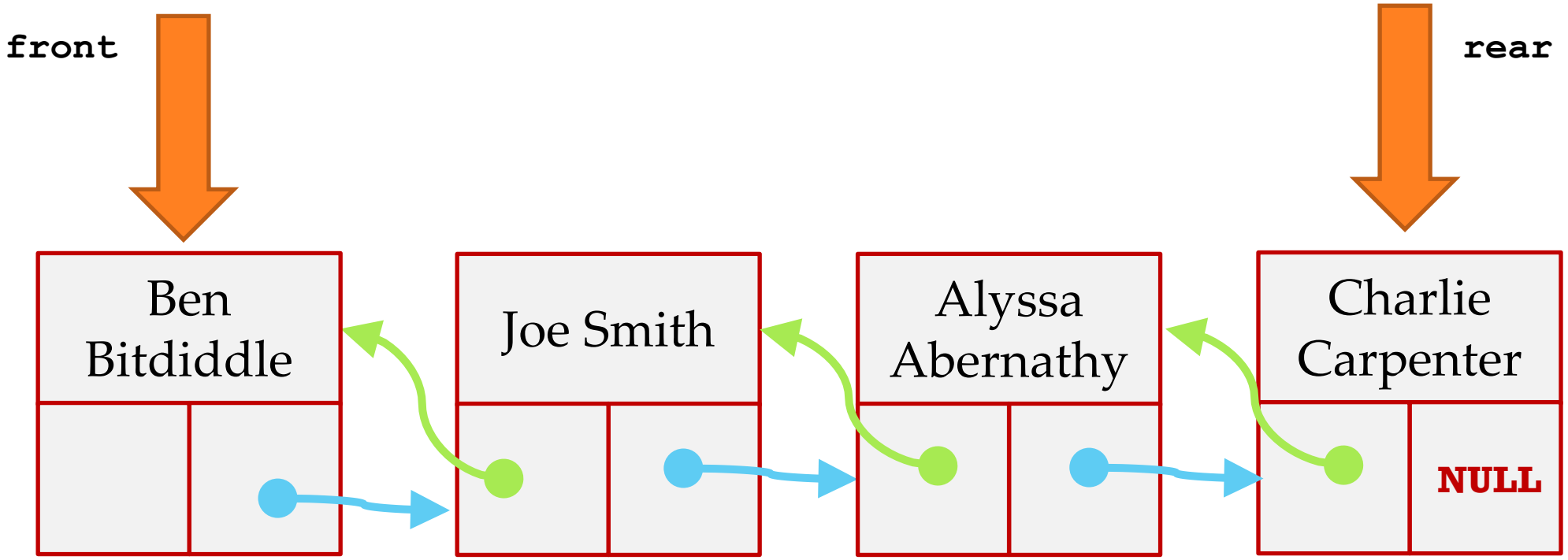


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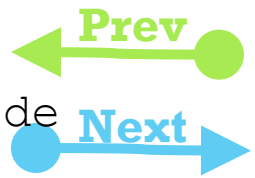

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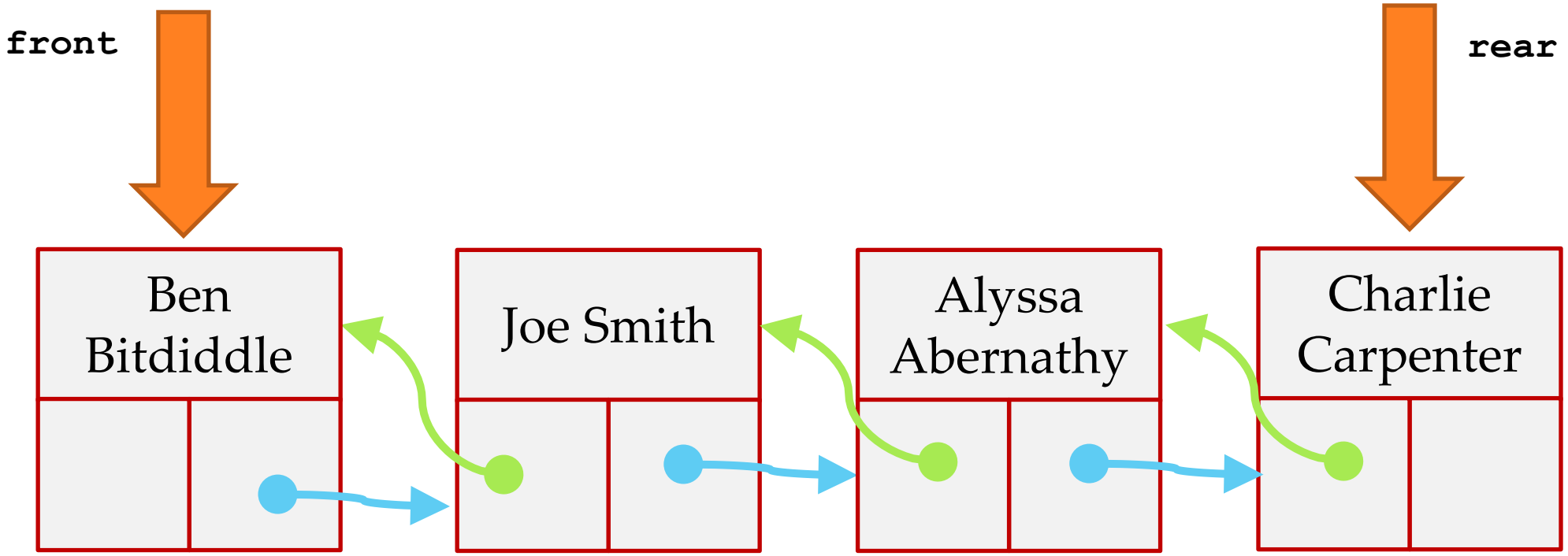


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remember the name
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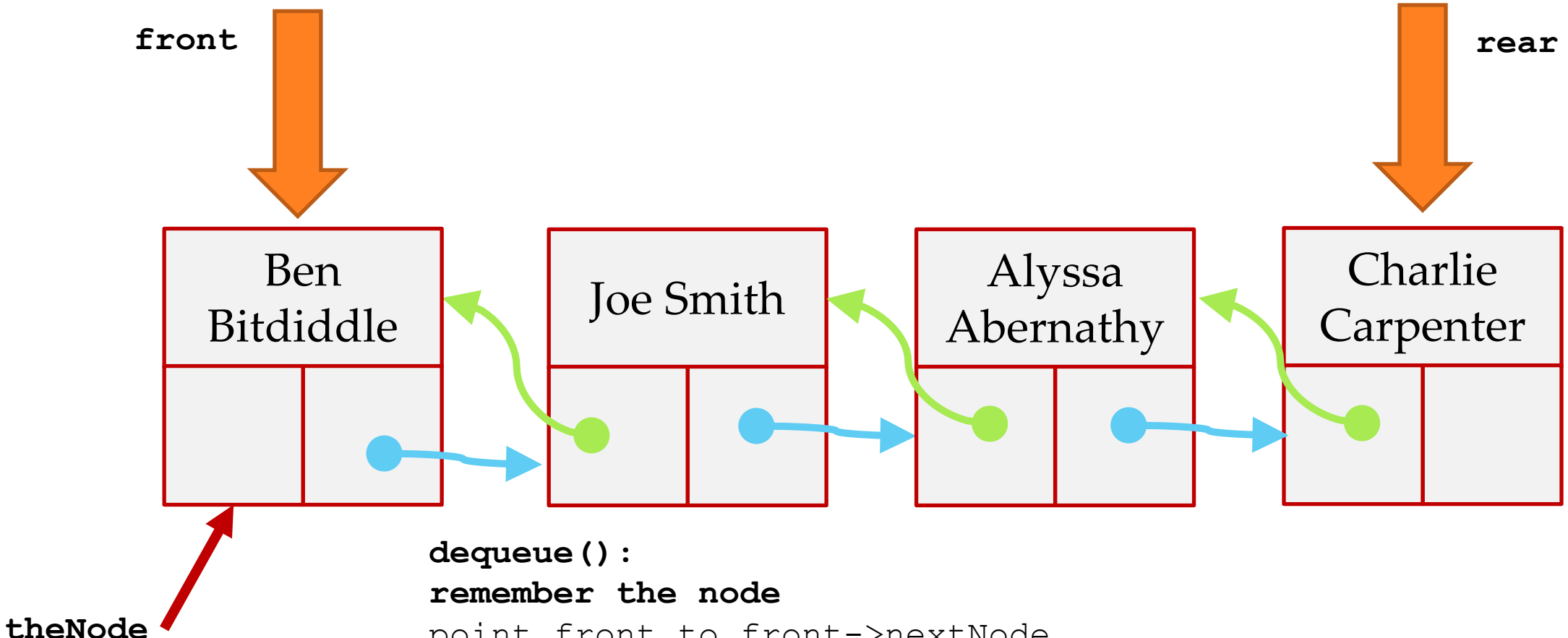


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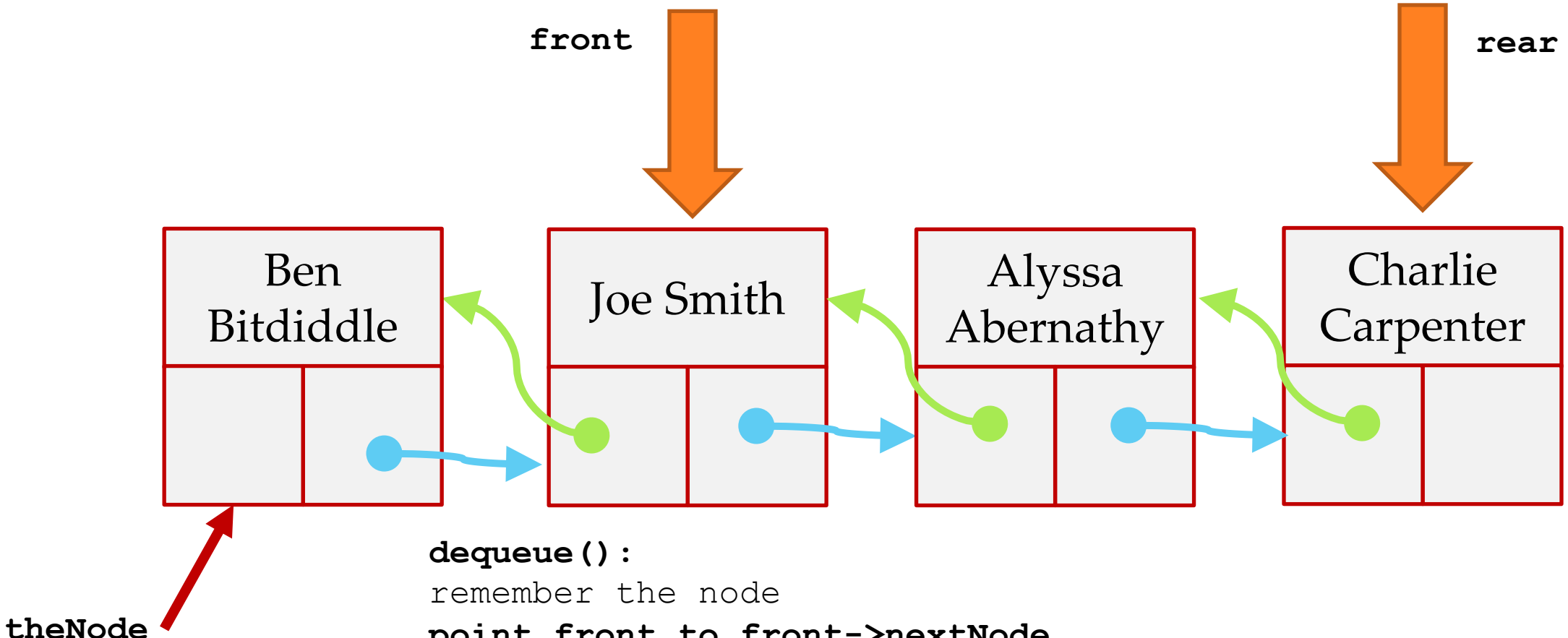


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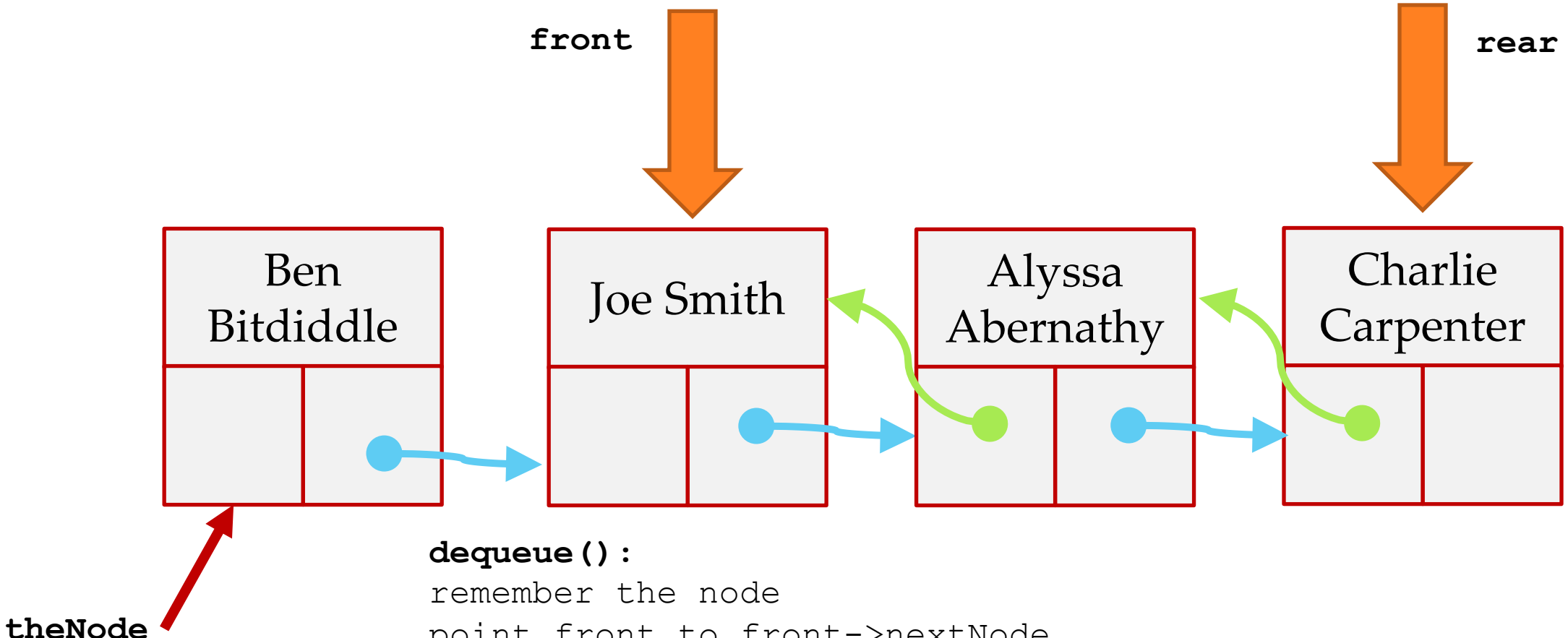


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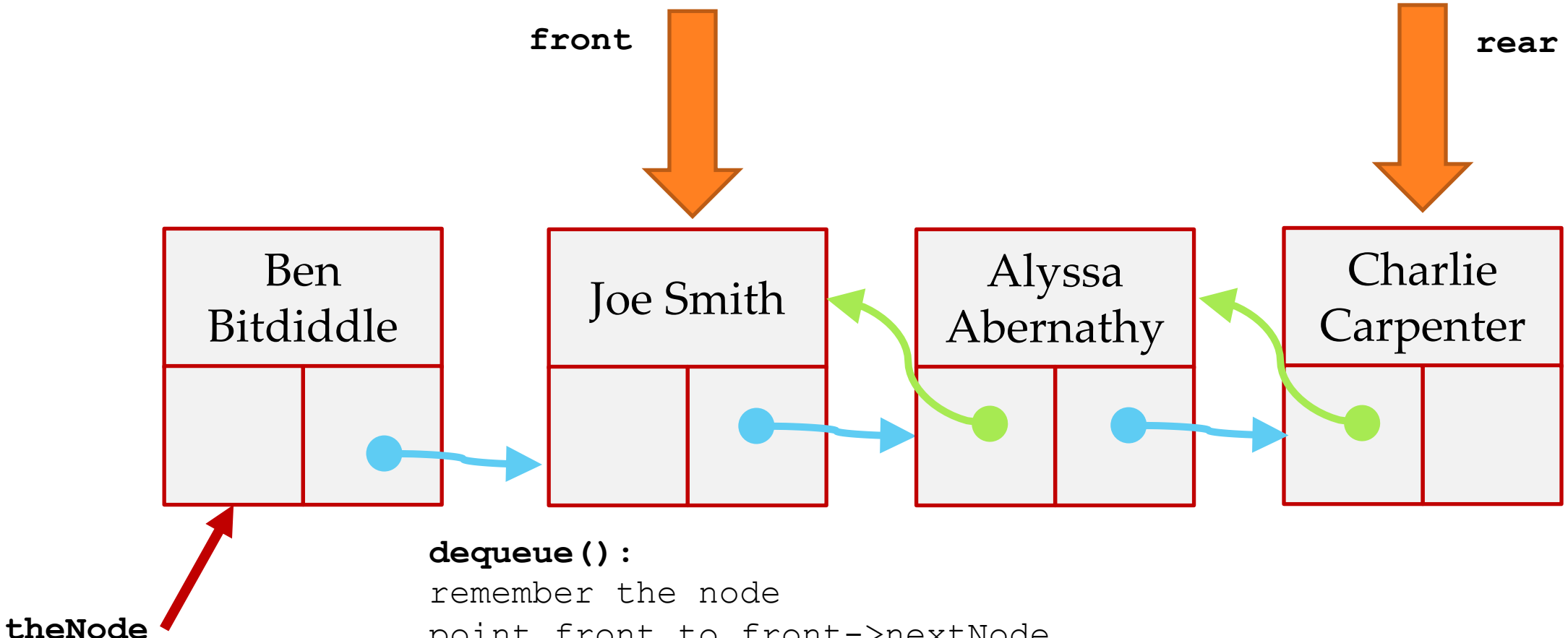


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dequeue():
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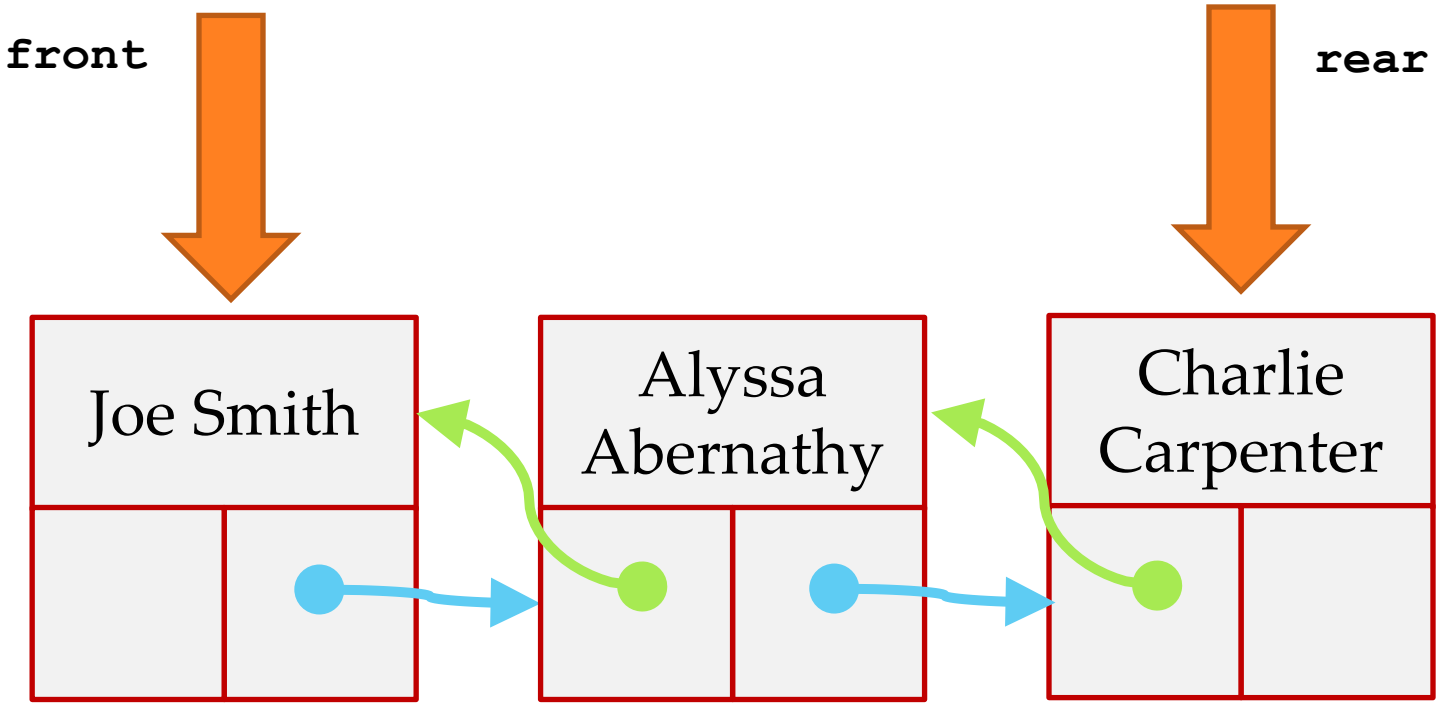
Prev

Next

# Dequeue: Removing an element

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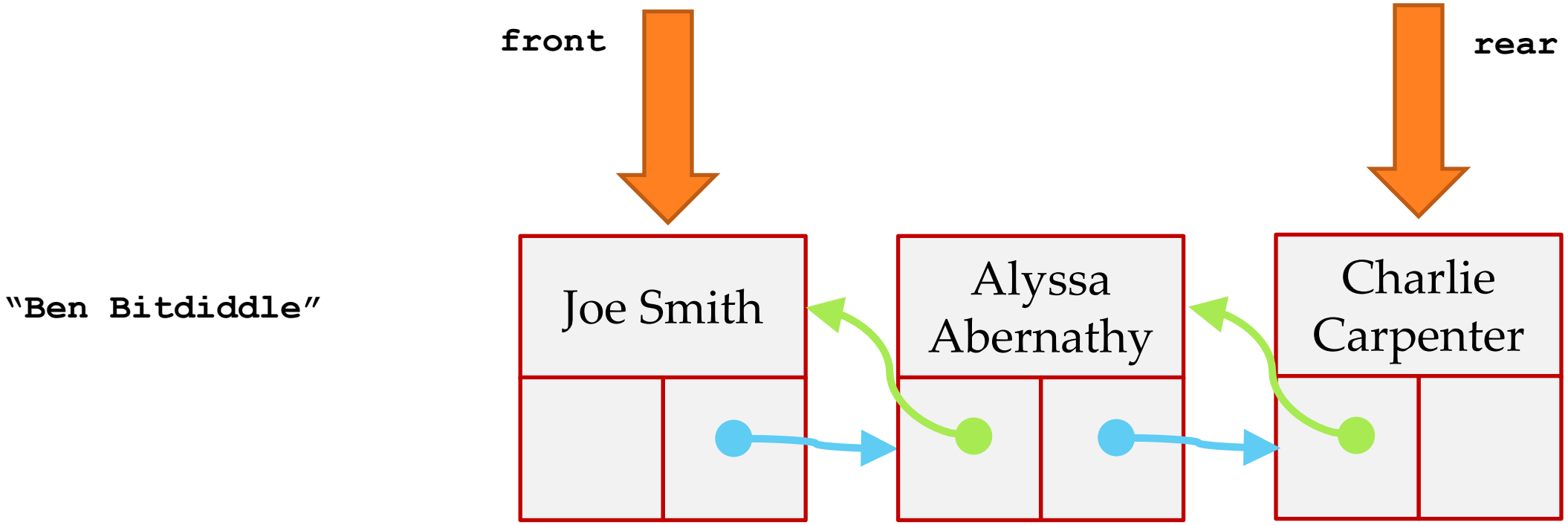


**dequeue():**

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remember the node
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**Now…**

**Do we have the same problems as using an array?**

- **No wrapping around: A linked list can grow [infinitely] in either direction!**

# Queue Operations

- **`enqueue()`**: Put an element in the queue
- **`dequeue()`**: Get the next element out of the queue
- **`front()`**: Look at the element at the front
- **`back()`**: Look at the element at the back/last inserted
- **`create()`**: Create the queue
- **`destroy()`**: Destroy the queue

# Queue Operations in C

- `char* dequeue(queueOfCustomers*);`
- `void enqueue(char* customer, queueOfCustomers*);`
- `char* front(queueOfCustomers*);`
- `char* back(queueOfCustomers*);`
- `queueOfCustomers* create();`
- `void destroy(queueOfCustomers*);`

```
struct queueOfCustomers{
    CustomerNode *front;
    CustomerNode *rear;
    int size;
}
```

# Implementing Queue Operations in C: create()

- `queueOfCustomers* create();`

```
queueOfCustomers* create(){
        // Allocate space on the heap
        // Initialize anything
        // Return pointer to new queue
}
```

```
struct queueOfCustomers{
    CustomerNode *front;
    CustomerNode *rear;
    int size;
}
```

# Implementing Queue Operations in C: destroy()

- `void destroy(queueOfCustomers*);`

```
void destroy(queueOfCustomers* customerQueue){
      // Free anything that hasn't been freed

      // Free the queue
      free(customerQueue);
}
```

```
struct queueOfCustomers{
   CustomerNode *front;
   CustomerNode *rear;
   int size;
}
```

# Implementing Queue Operations in C: enqueue()

- `queueOfCustomers* enqueue(char*, queueOfCustomers*);`

```
void enqueue(char* newCustomer, queueOfCustomers* queue){
        // Update the head index

        // Put the element in the array

        // Return queue (by convention
}
```

```
struct queueOfCustomers{
    CustomerNode *front;
    CustomerNode *rear;
    int size;
}
```

# Implementing Queue Operations in C: dequeue()

- `char* dequeue(queueOfCustomers*);`

```
char* dequeue(queueOfCustomers* queue){

}
```

```
struct queueOfCustomers{
   CustomerNode *front;
   CustomerNode *rear;
   int size;
}
```

# Implementing Queue Operations in C: front()

- `char* front(queueOfCustomers*);`

```
char* front(queueOfCustomers* queue){

}
```

```
struct queueOfCustomers{
   CustomerNode *front;
   CustomerNode *rear;
   int size;
}
```

# Implementing Queue Operations in C: rear()

- `char* rear(queueOfCustomers*);`

```
char* rear(queueOfCustomers* queue){

}
```

```
struct queueOfCustomers{
   CustomerNode *front;
   CustomerNode *rear;
   int size;
}
```

# Let's play with code…

- https://github.ccs.neu.edu/CS5002SEAF17/resources/blob/master/lect…

- (CS5002 resources repo on Github; lect10)

# What about implementing a Queue with a Stack?

# It's possible: think about it, and we'll look at it next time.

# Now, what if our Queue held patients instead of customers?

# Last time…

- Stacks

# Linked Lists

# Summary

**Stack**

- Primary Operations
  - Push
  - Pop
  - Peek
- Helper Operations
  - Create
  - Destroy
  - IsEmpty
  - IsFull

**Linked List**

- Primary Operations
  - Add
  - Remove
- Helper Operations
  - Create
  - Destroy
  - IsEmpty
  - Contains(Node), Contains(Data)
  - InsertBefore(), InsertAfter()
  - AddAtHead(), AddAtTail()

# Summary

**Stack**

- The abstraction is more important than the implementation
  - We implemented as an array; could also use a list.

**Linked List: Alternative to Array**

- Could be single or double linked
  - We talked about single
  - We implemented double
  - Code for single is in Github
- The List is really just a pointer to a single node
  - We implemented a wrapper struct that helped us keep track of the head
  - We can add metadata to that struct to help
    - Such as NumItems, ptr to LastNode.

# Arrays Versus LinkedList

**Array**

- Contiguous Memory
- You have to know the size before you create it
  - If you don't use all the memory allocated, you're wasting it
  - If you don't allocate enough, oops.

**LinkedList**

- Nodes can be non-contiguous
- You can keep growing the list, taking as much memory as you need but not more than you need

# Summary

- Queue
  - LIFO data structure
- Queue Operations:
  - enqueue() or insert(): puts element at back of list
  - dequeue() or remove(): returns element at front of list
  - front() or rear(): looks at the front/rear element
  - create()/destroy()

# Comparing Data Structures

| | Stack | Linked List | Queue | Tree |
|---|---|---|---|---|
| **Type** | Linear | Linear | Linear | Tree/graph |
| **Insert action** | Puts element at top | Inserts element where specified | Puts element at back | … |
| **Insert operation** | push() | insert() | enqueue() | … |
| **Remove action** | Returns element at top | Removes element as specified | Returns element at front | … |
| **Remove operation** | pop() | remove() | dequeue() | … |
| **Notes** | LIFO | Arbitrary length (not constrained by array size) | FIFO | … |
| | | | | |

# Runtime, Memory

| | Stack (Array) | Linked List | Queue (Llist) |
|---|---|---|---|
| **Memory** | O(k >= n)<br>*[k = max size]* | O(n) | O(n) |
| **Insert** | O(1) | O(1) *[insert beginning]*<br>O(n) *[insert elsewhere]* | O(1) |
| **Remove** | O(1) | O(1) | O(1) |
| **Find/ Contains** | N/A | O(n) | N/A |

# Next time:

- Sequences and Summations
- Trees
- More performance & efficiency