Linked Lists

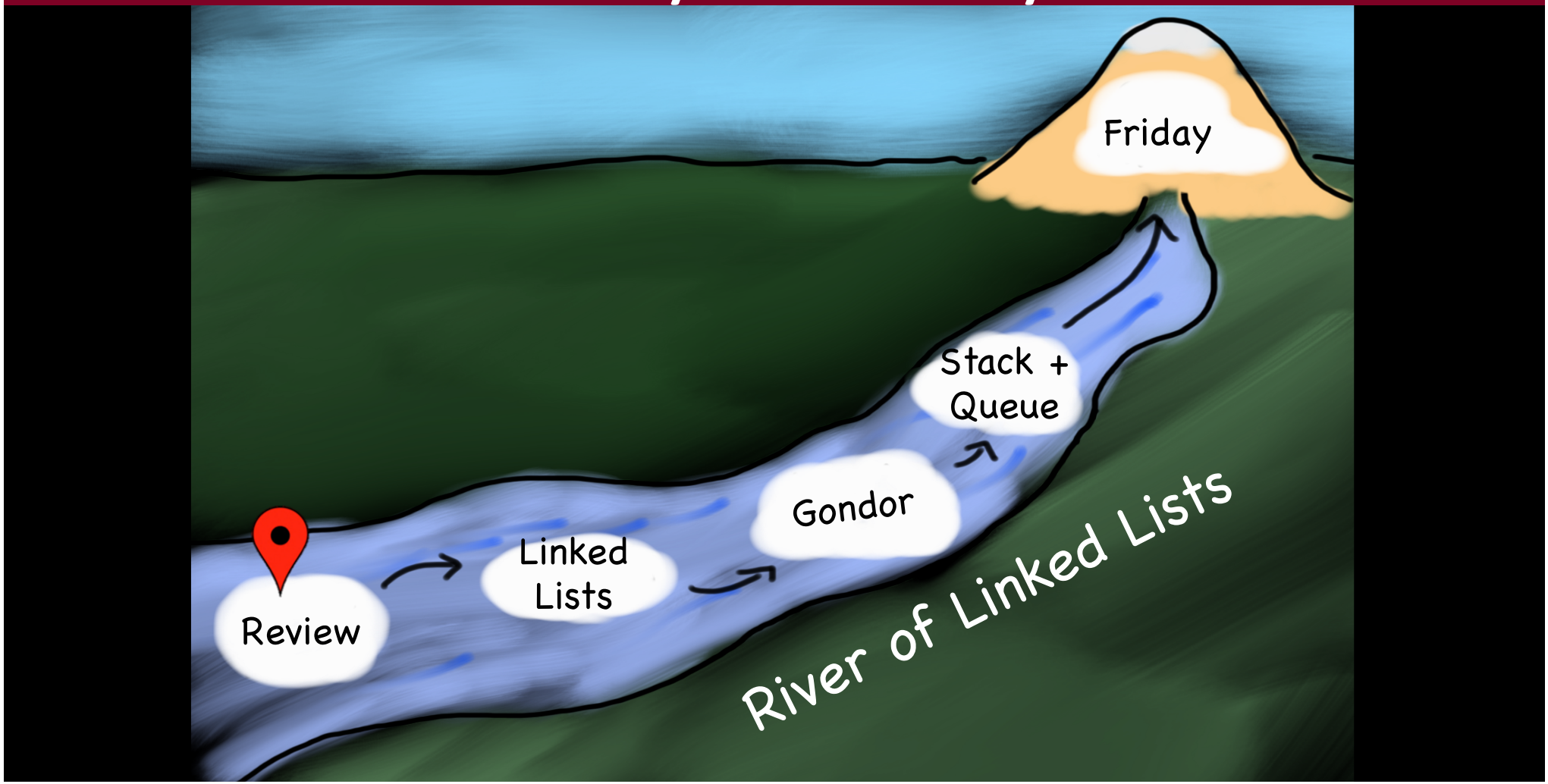
CS 106B

Programming Abstractions
Fall 2016
Stanford University
Computer Science Department

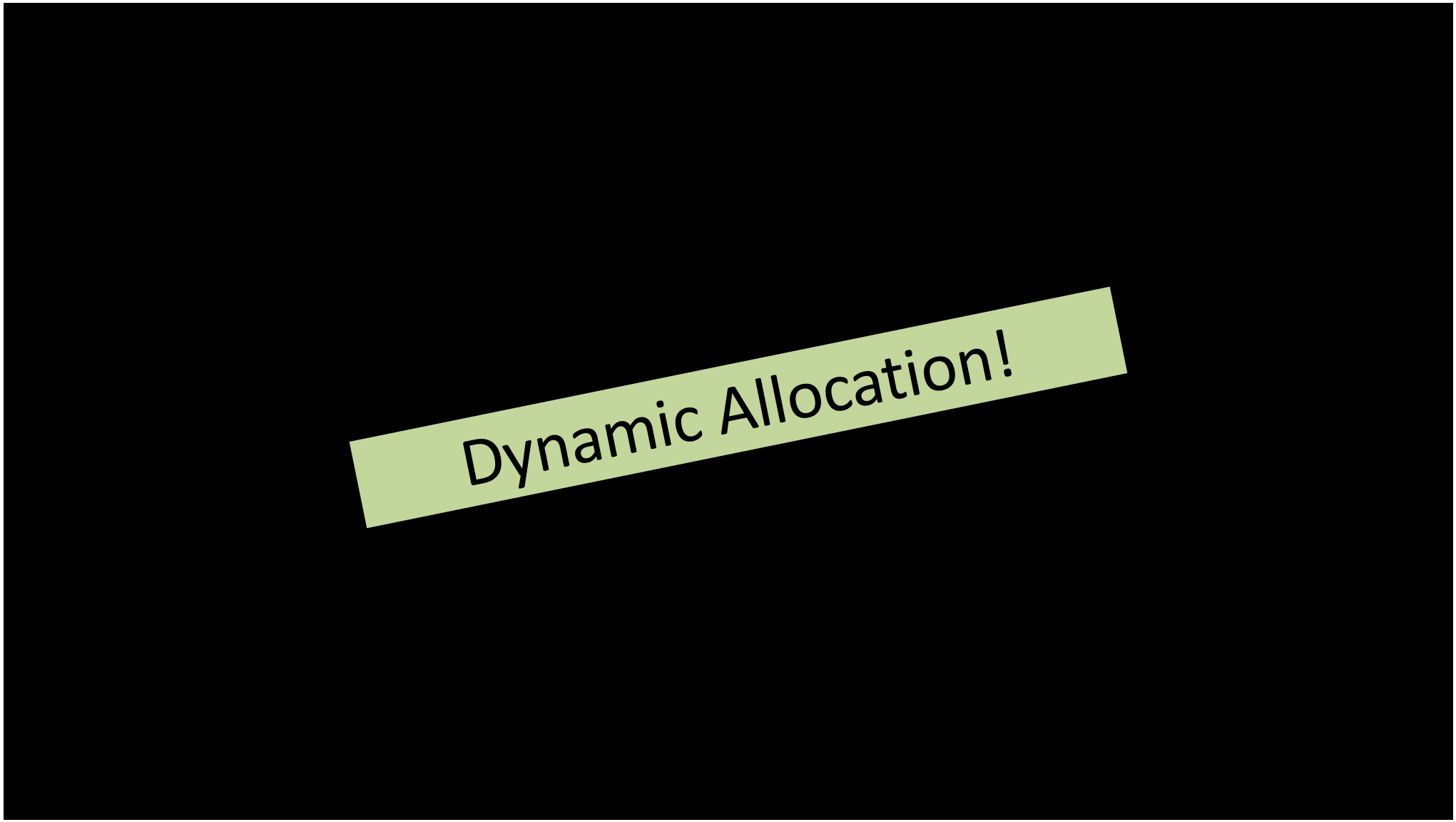
Today's Goals

1. Learn linked lists
2. See how Stack + Queue work
3. Get ready for trees…

Today's Journey



Announcement


Dynamic Allocation!

Pointers

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// dynamically request memory for a new GImage.
// calls the constructor.
// store the address of the new GImage.

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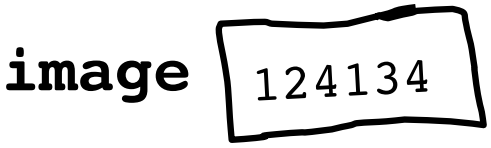

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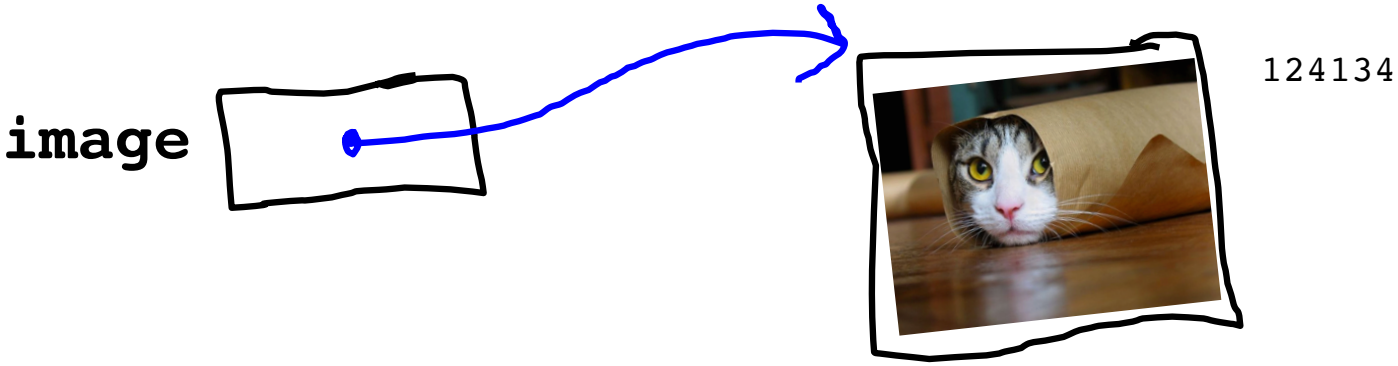


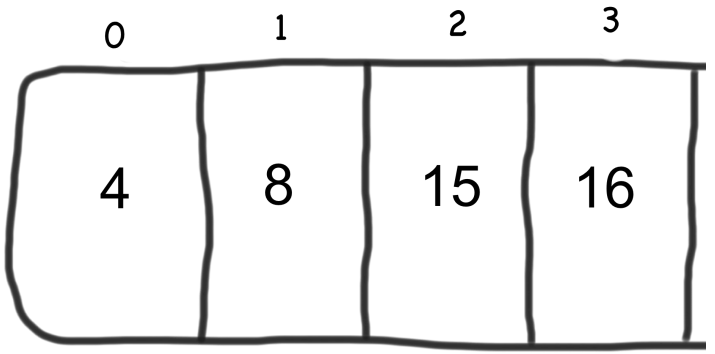
Pointers

Its easy to share large objects.

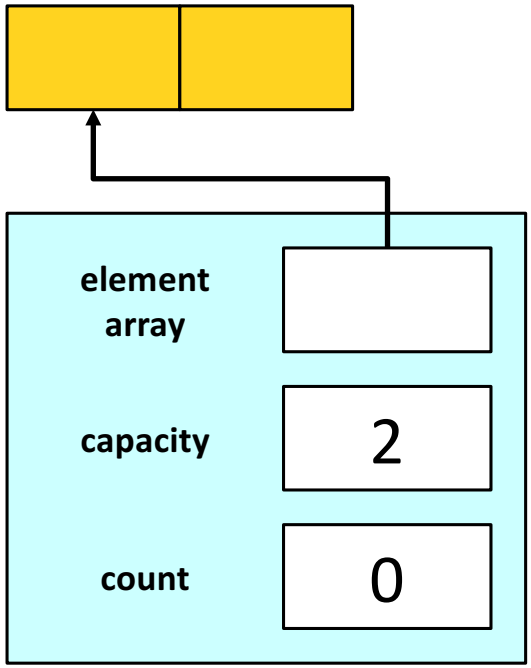
A pointer is like a URL. Not the actual page, the address of the page

Control over variable lifespan.

While the program is running, you can request more space.



The Actual Vector



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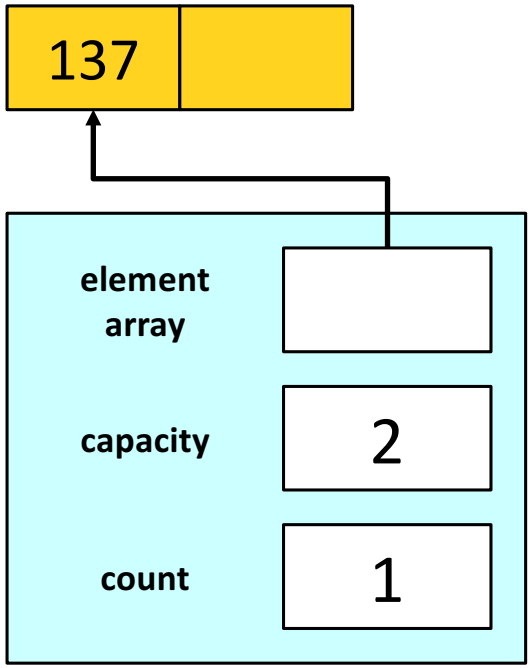

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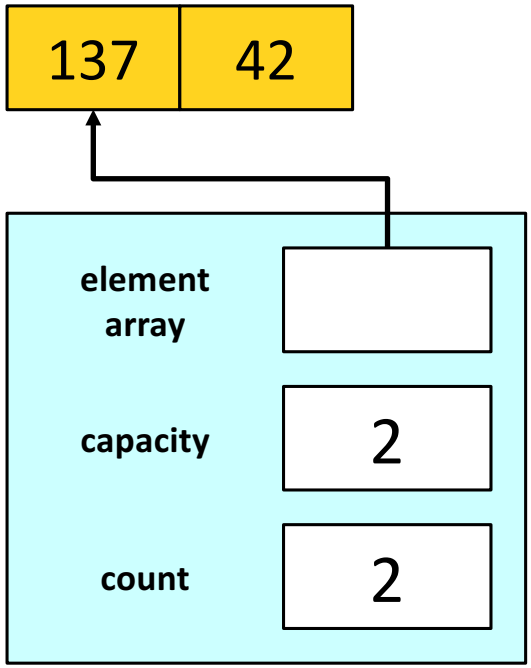

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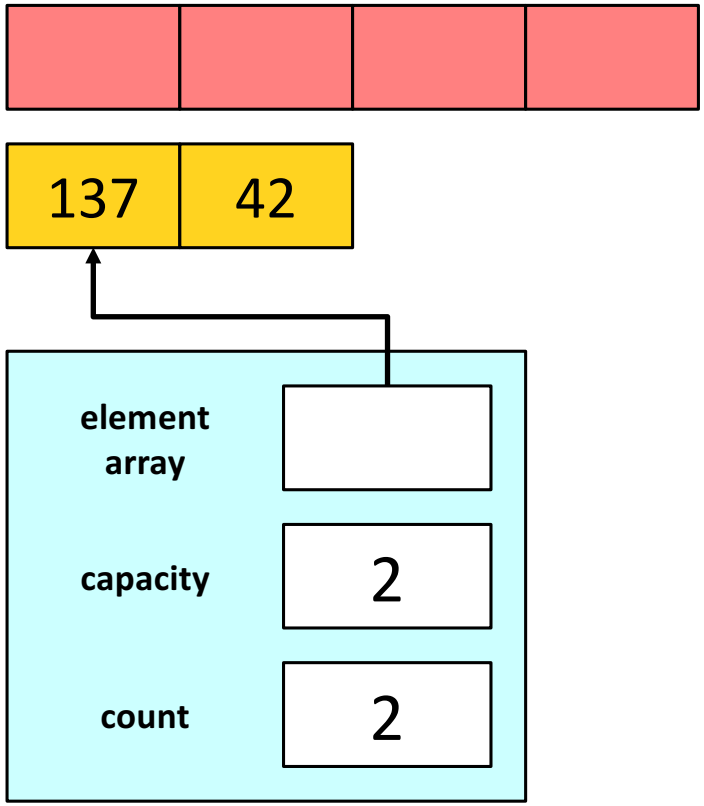

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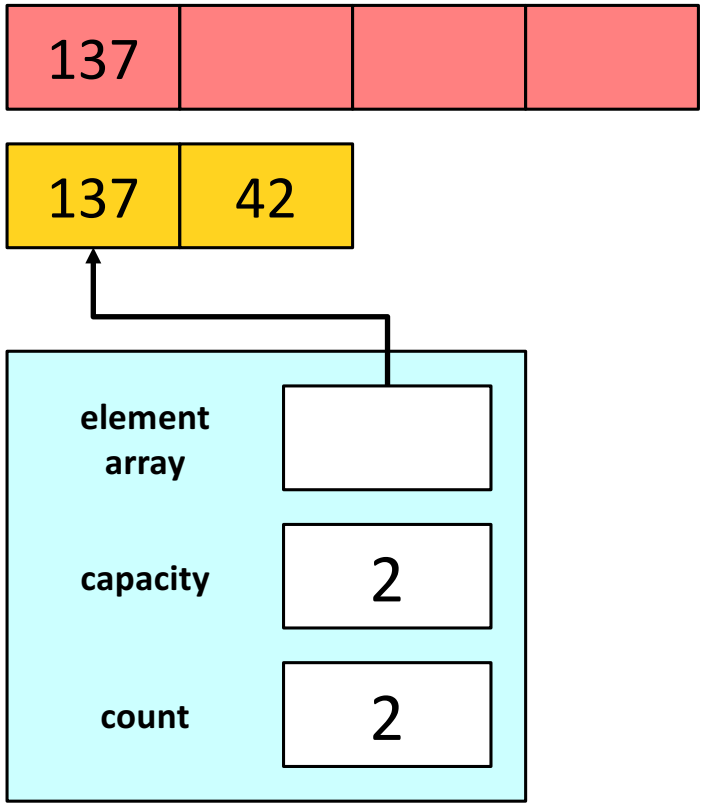

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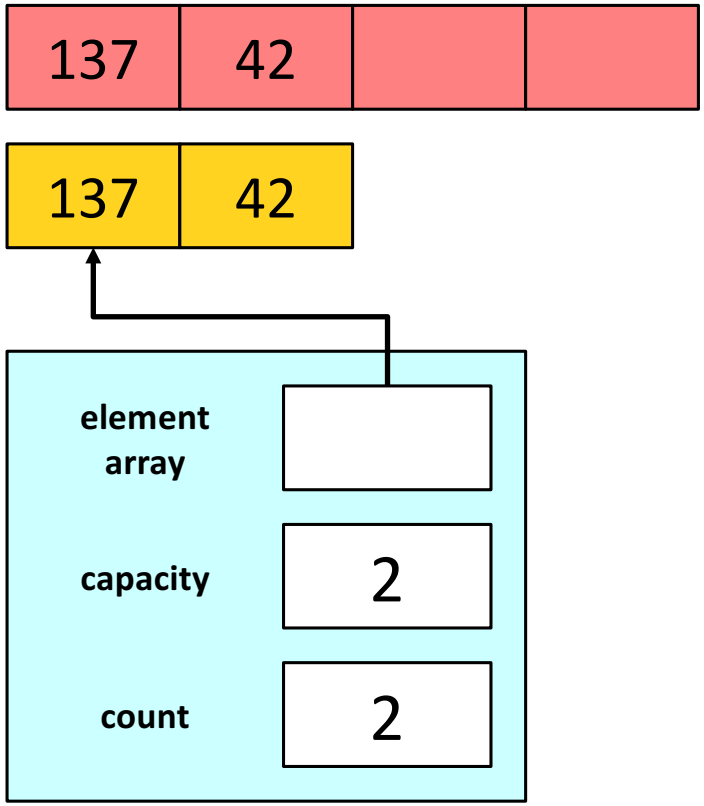

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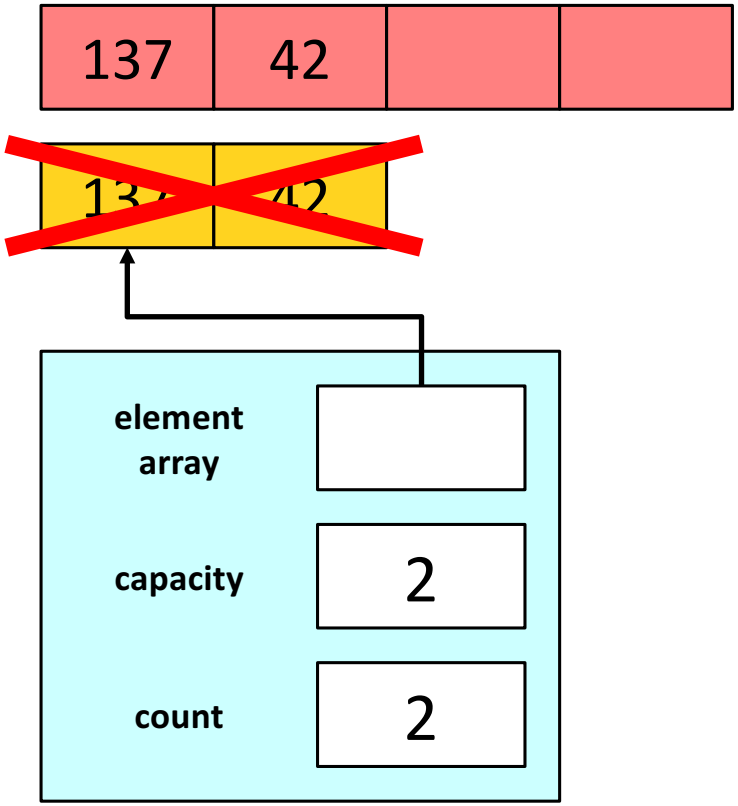

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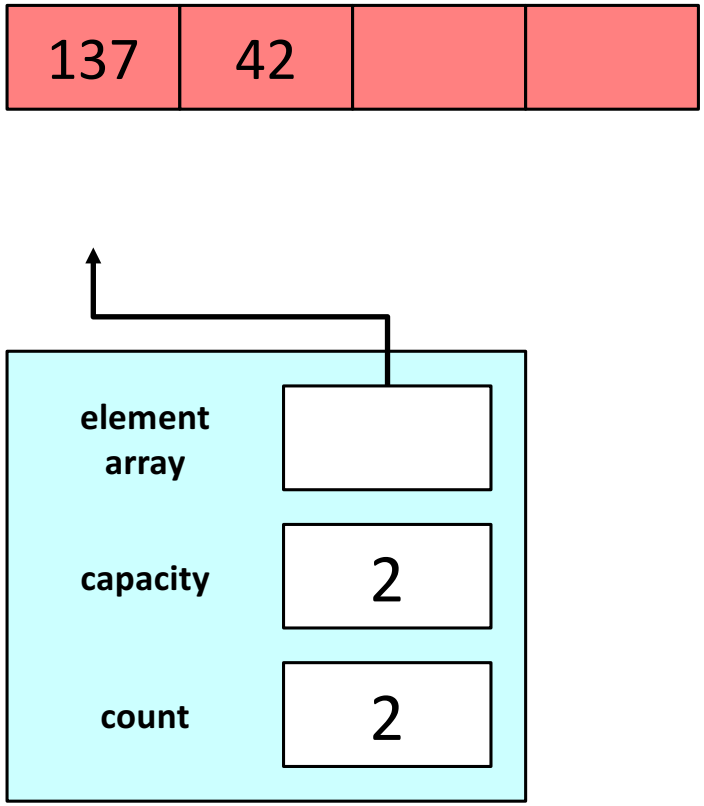

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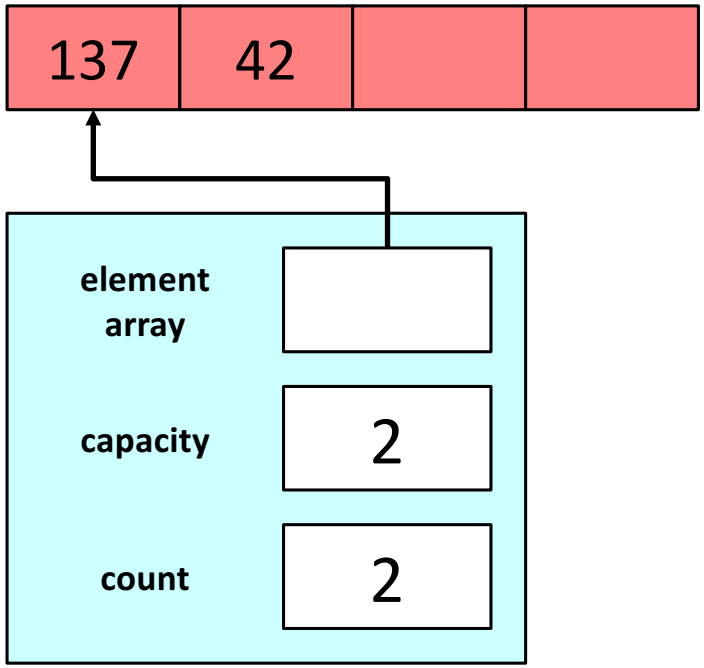

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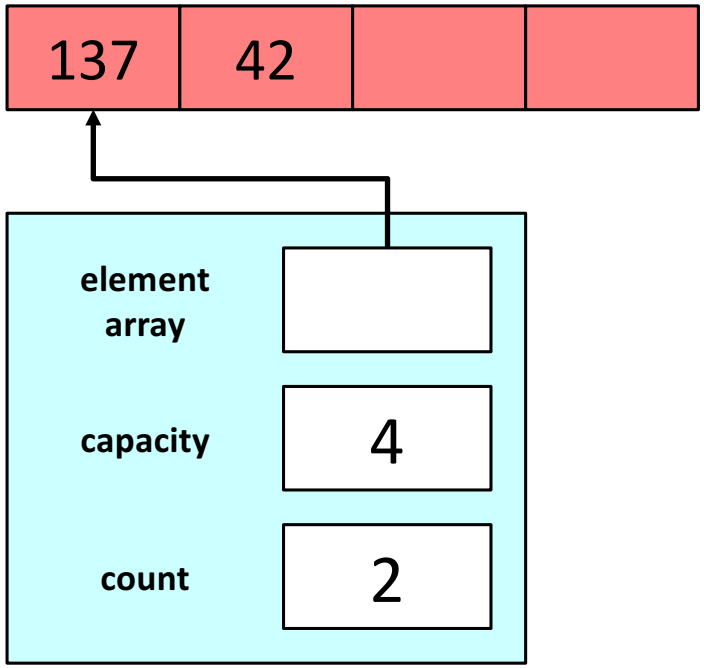

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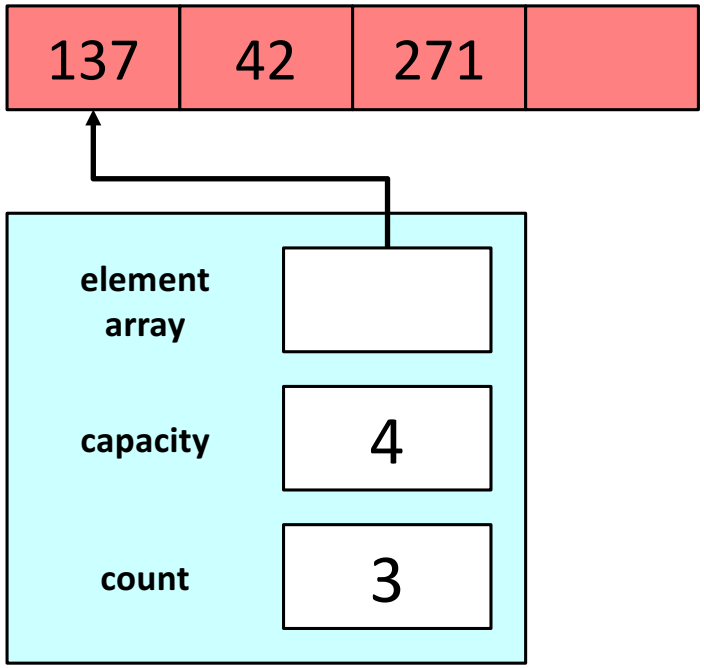

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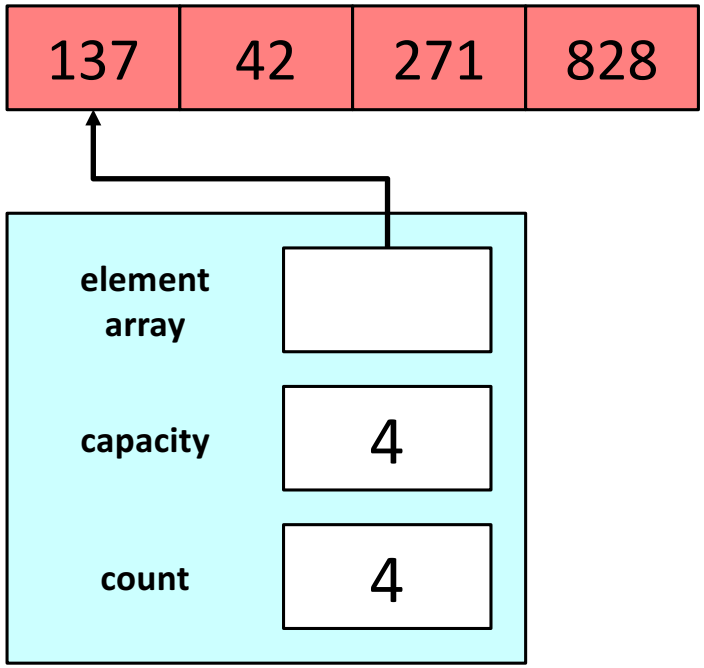

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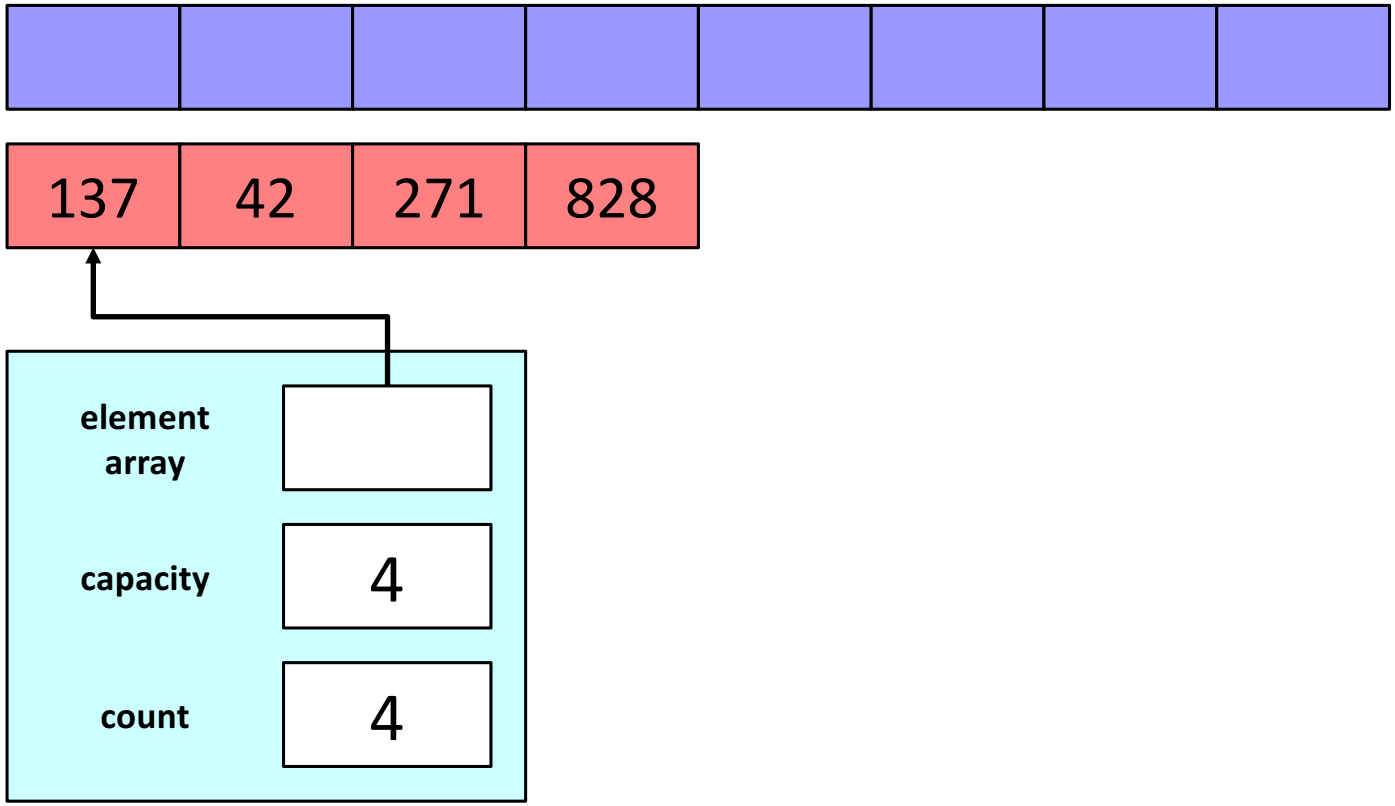

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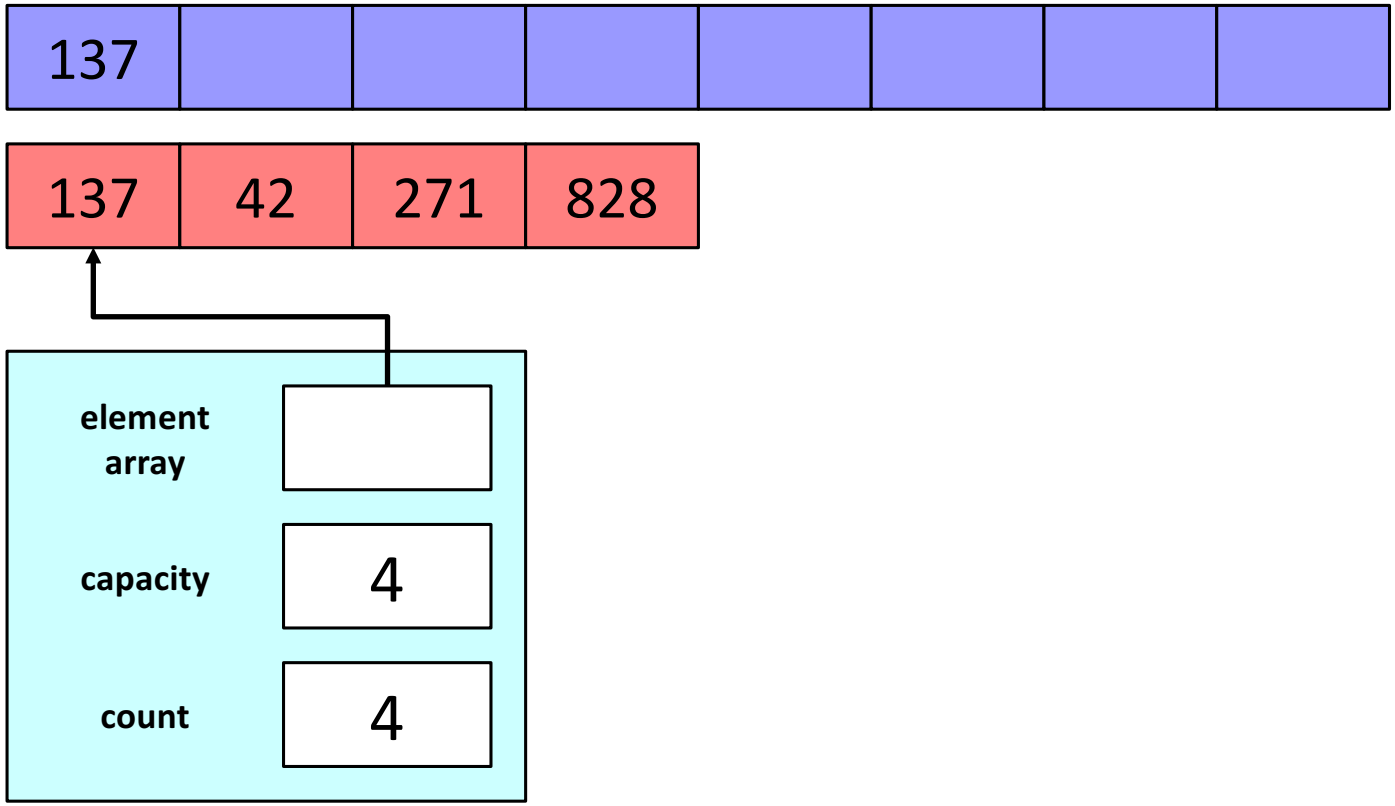

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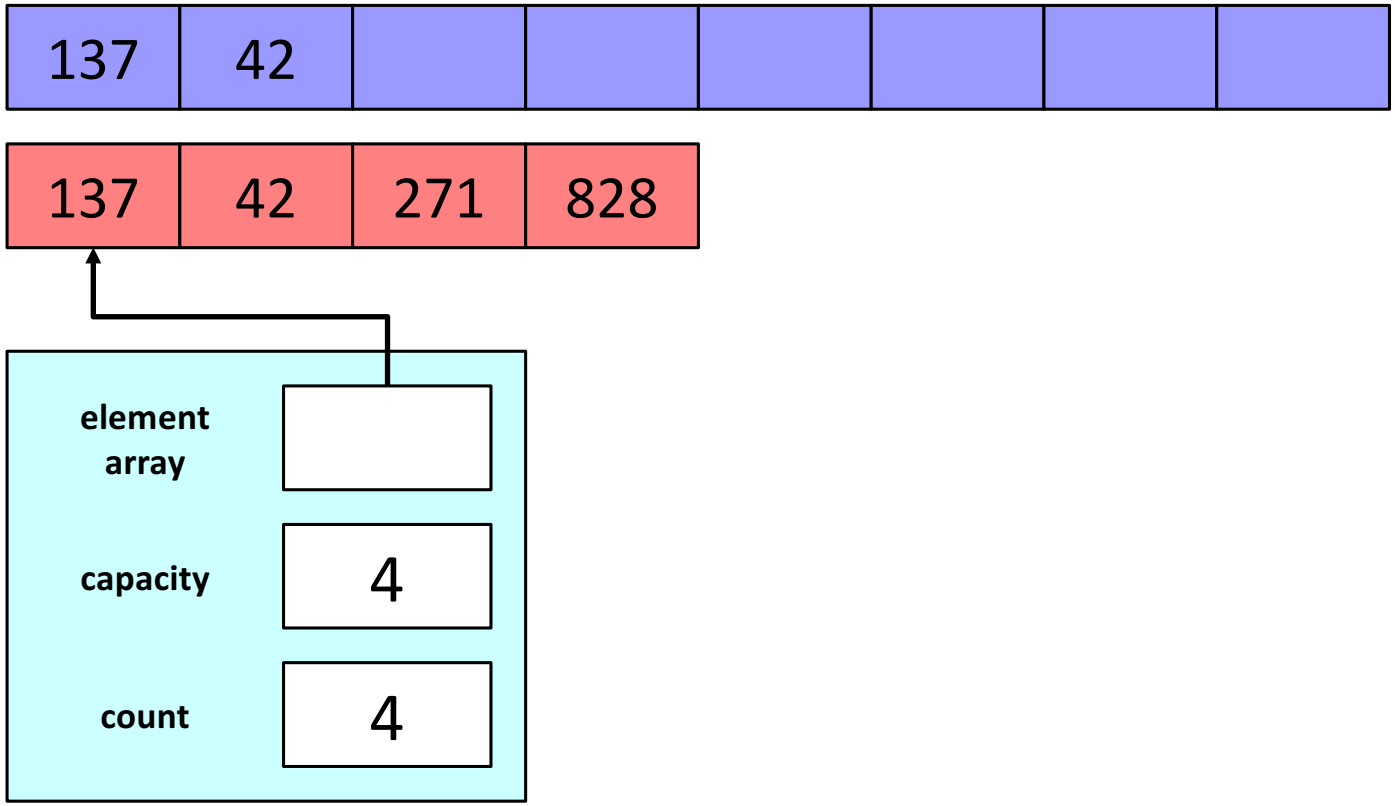

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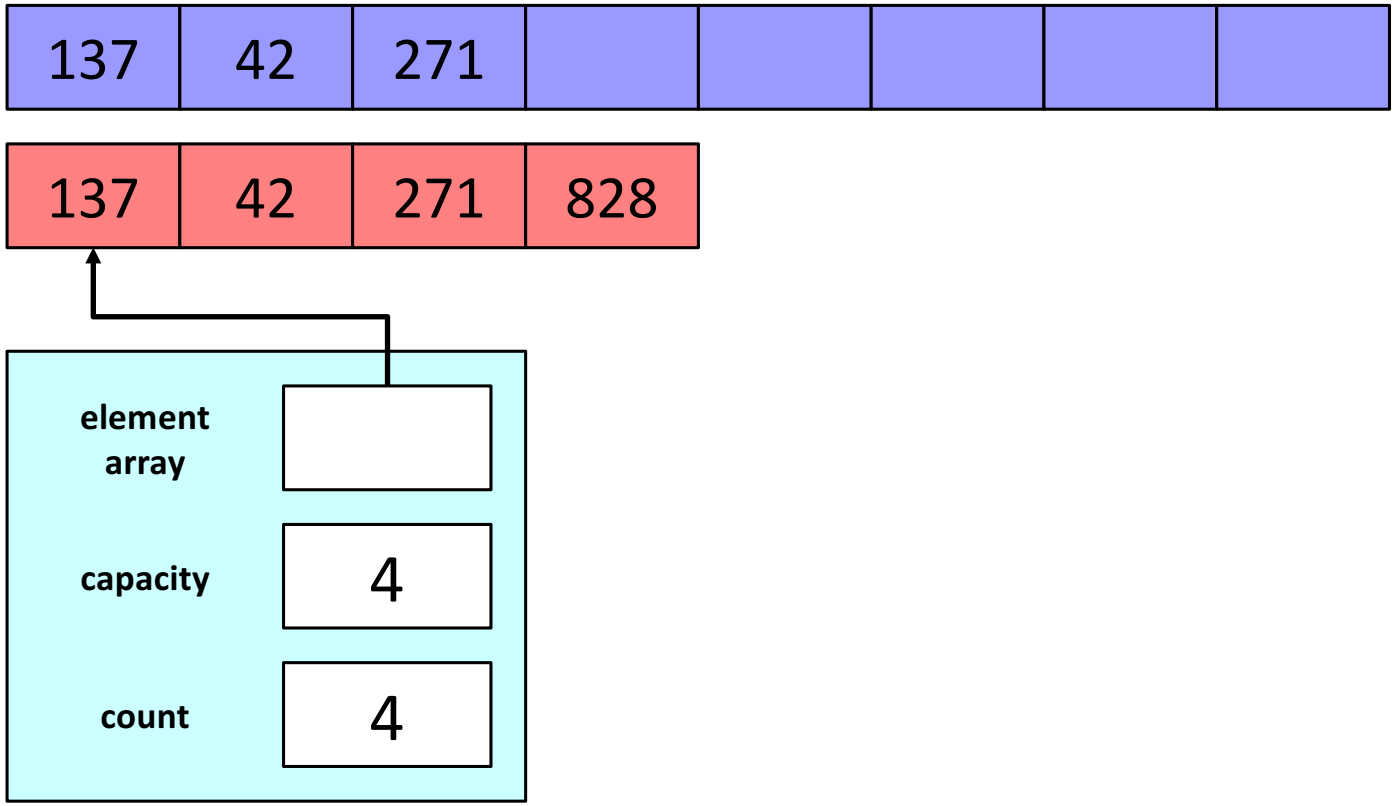

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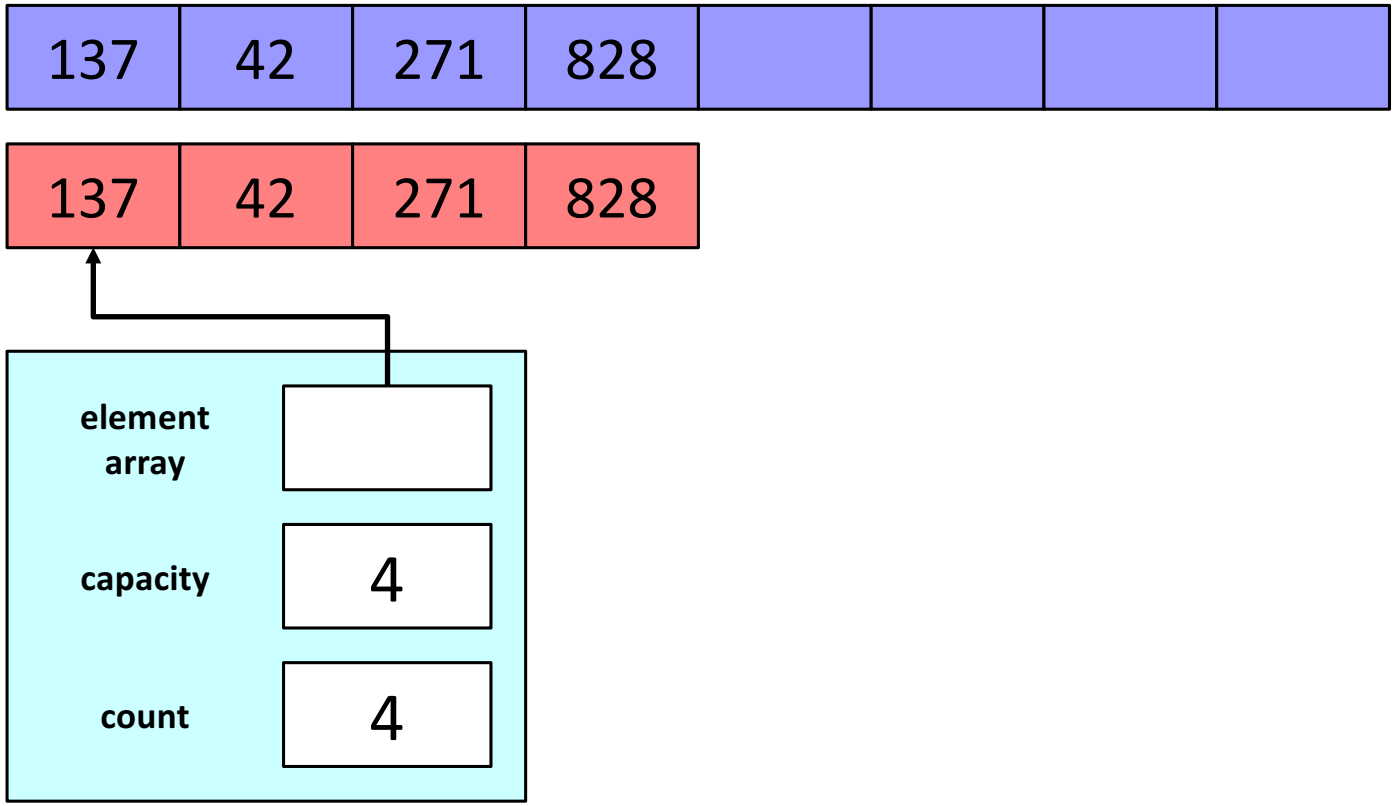

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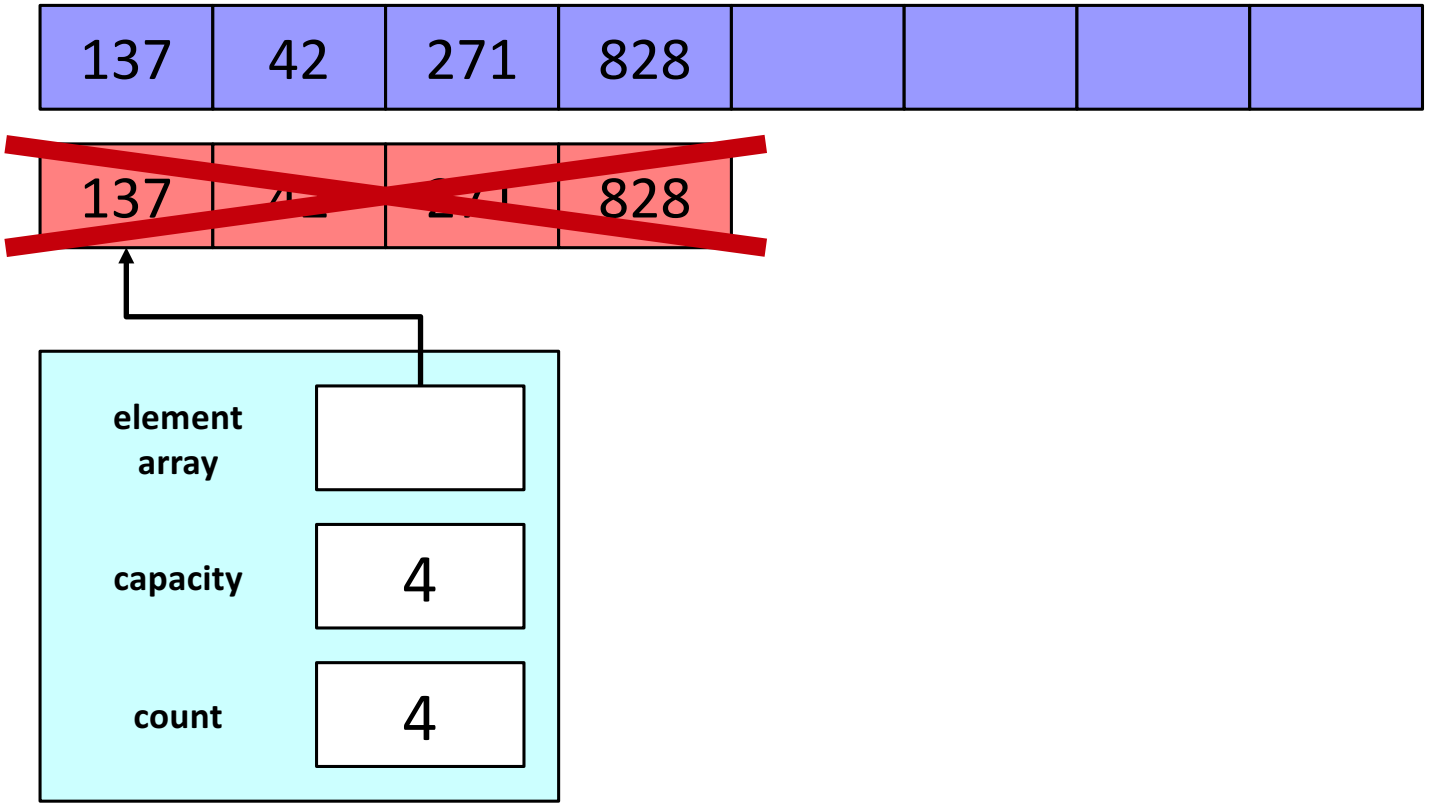

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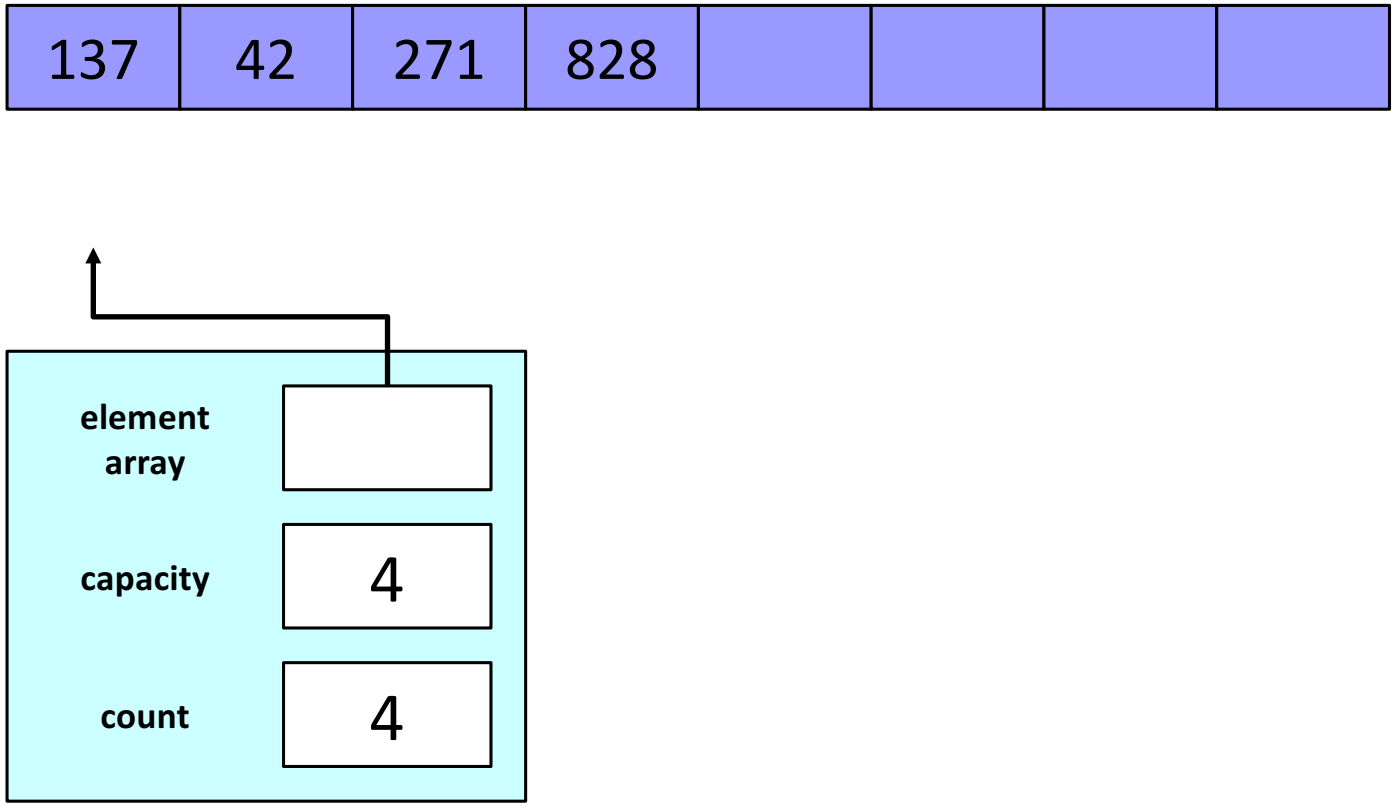

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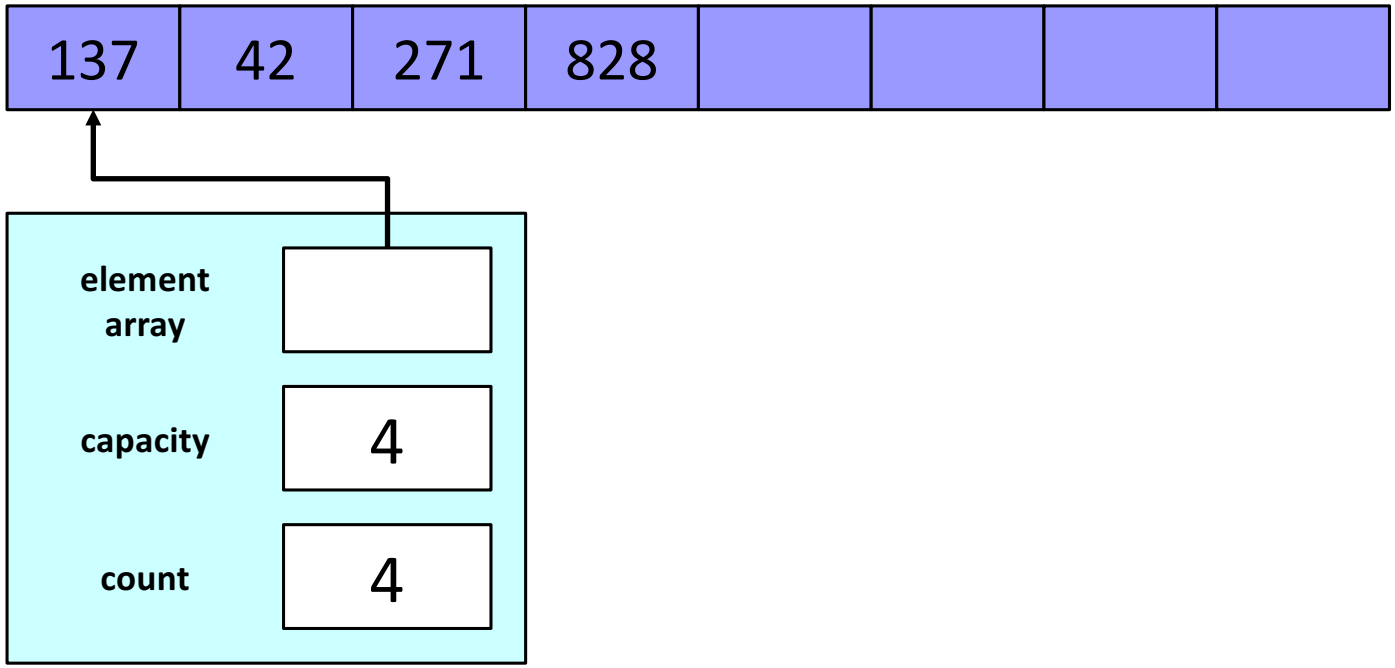

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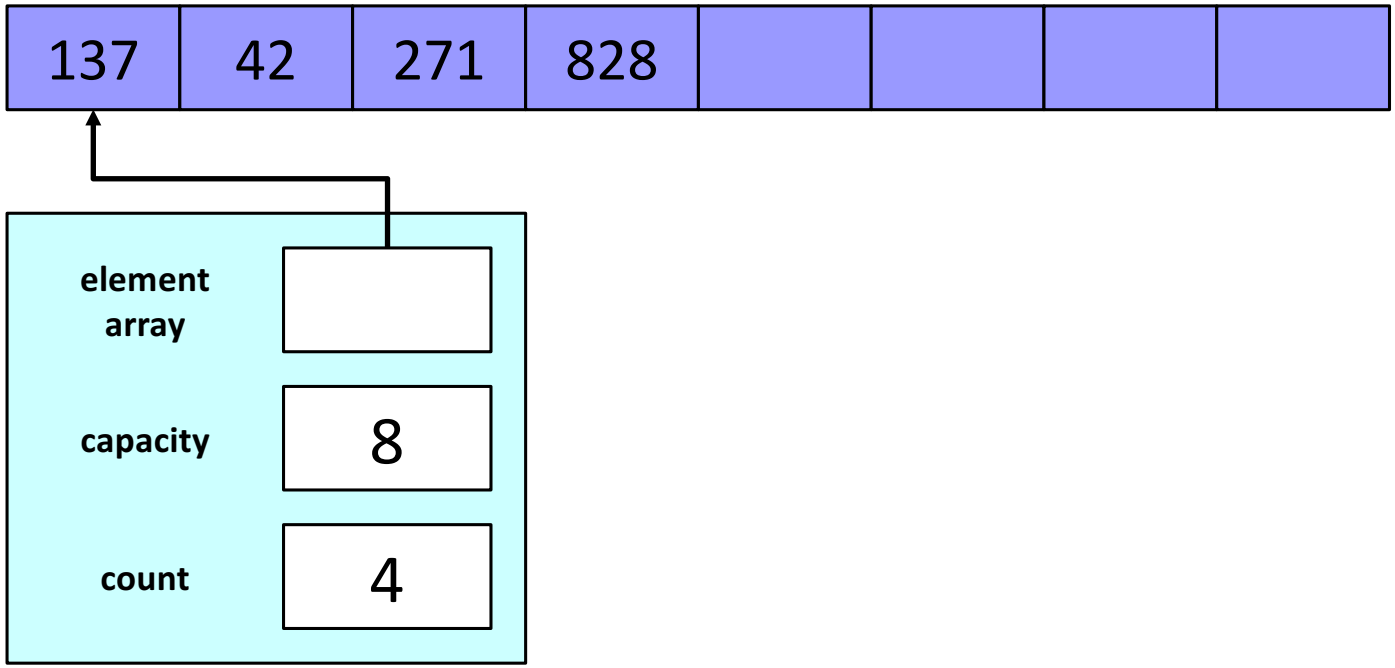

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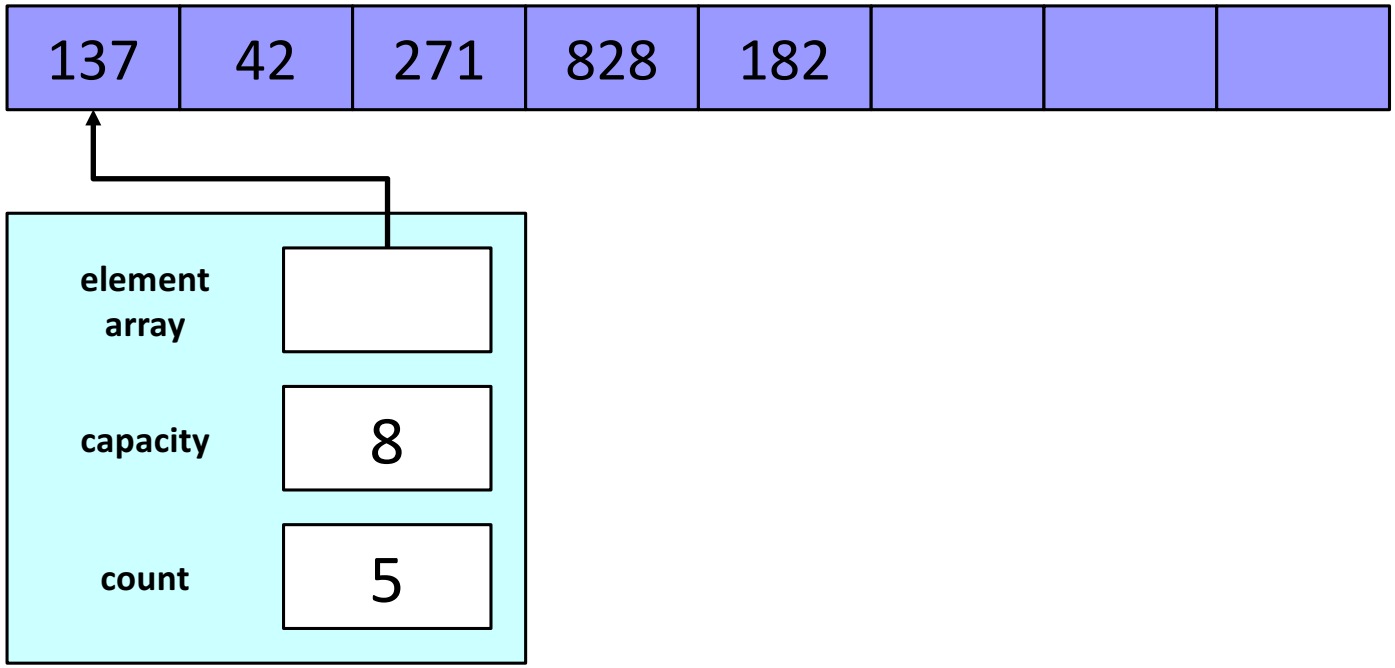

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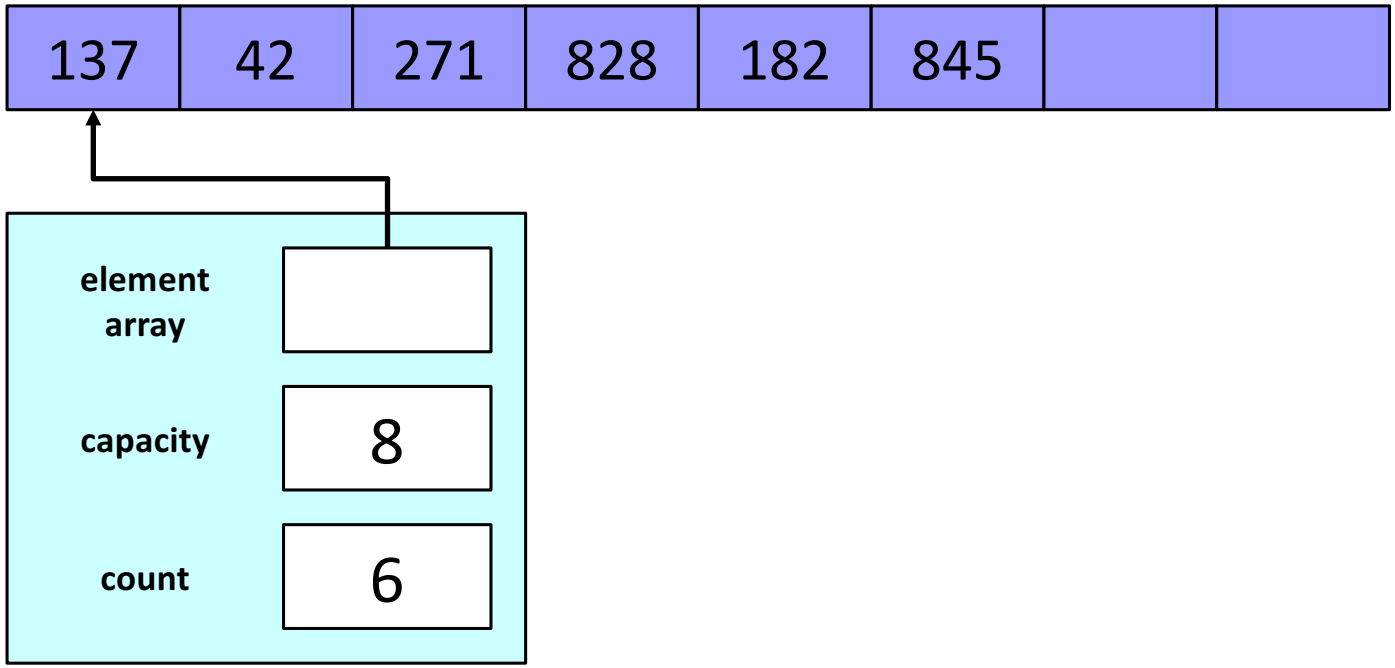

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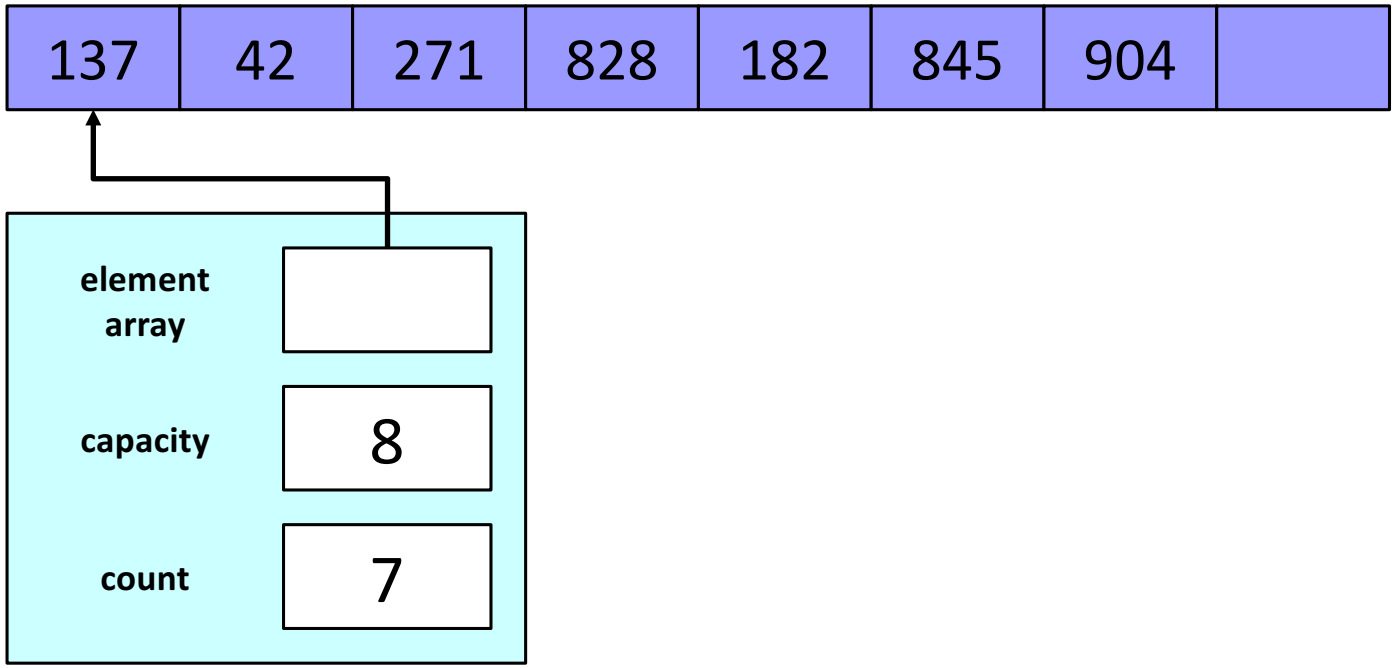

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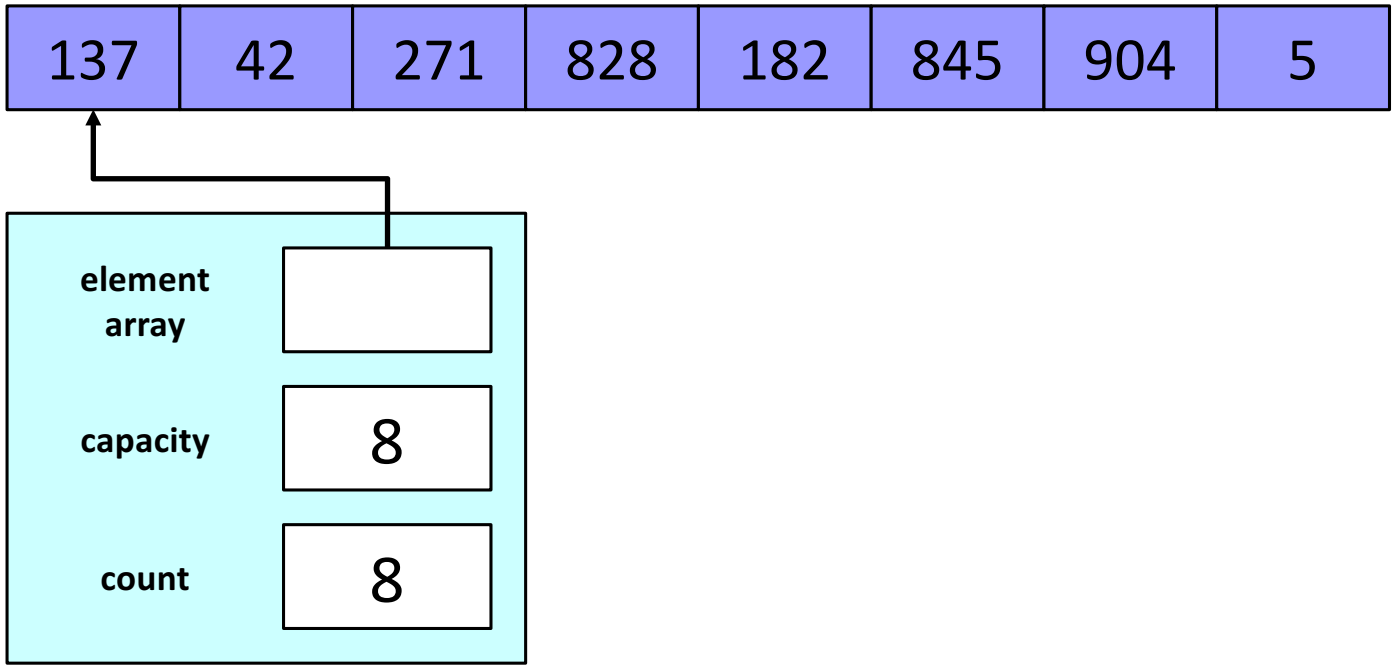

Vector Big O?

Big O of Get?

```
int VecInt::get(int index){
    return data[index];
}
```

Big O of Get?

$$\mathcal{O}(1)$$

Big O of Get?

Add?

Big O of Add?

```
void VecInt::add(int v){
    if(count == capacity) {
        expand();
    }
    elements[count] = v;
    count++;
}

void VecInt::expand() {
    capacity *= 2;
    int * newData = new int[capacity];
    for(int i = 0; i < count; i++) {
        newData[i] = elements[i];
    }
    delete[] data;
    elements = newData;
}
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Worst Case

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}
```

Worst Case

Big O of Add?

$$\mathcal{O}(n)$$

Remove?

Big O of Remove?

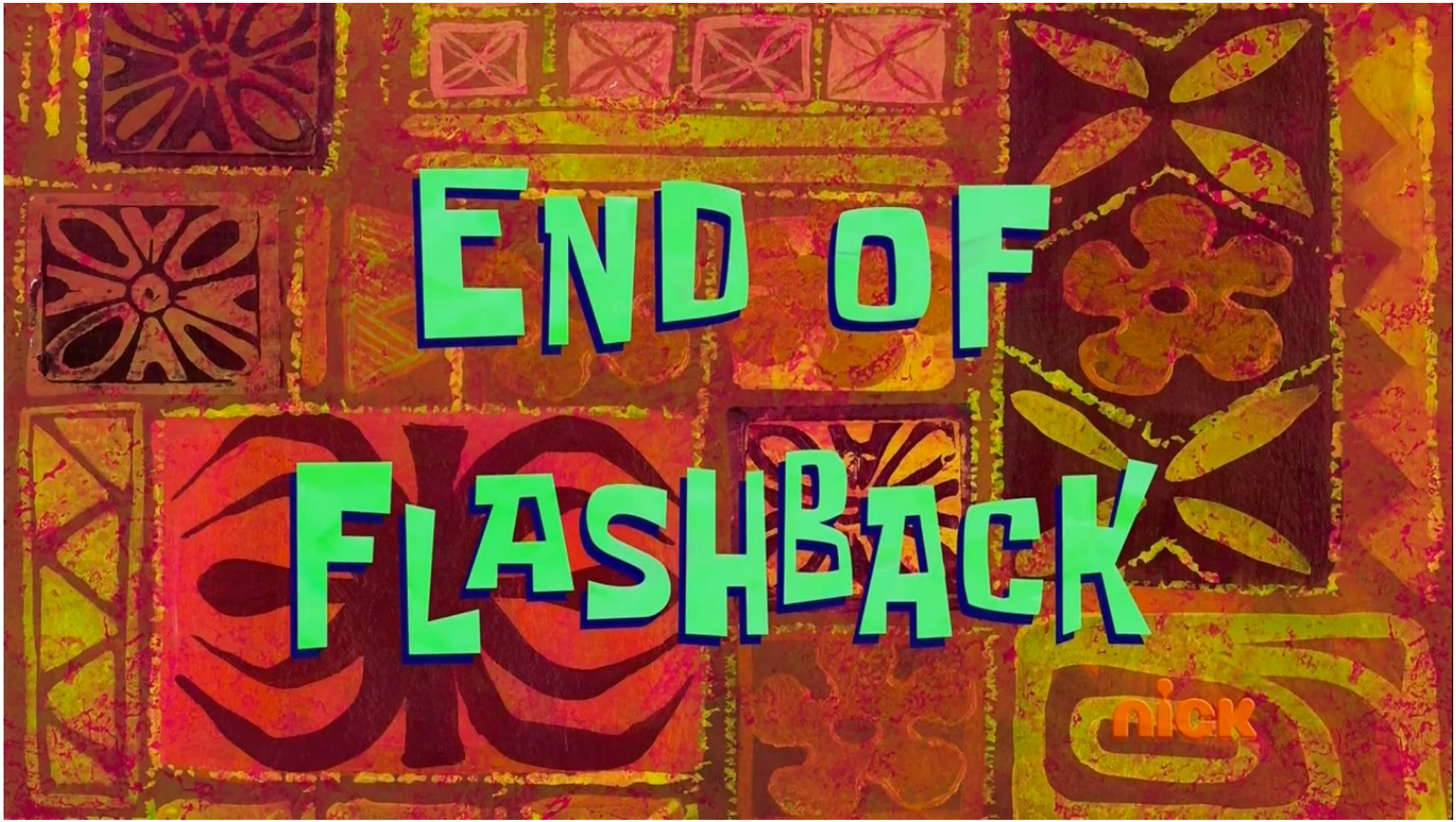
```
void VecInt::remove(int index){
    for(int i = index; i < count - 1; i++) {
        elements[i] = elements[i + 1];
    }
    count--;
}
```

Big O of Remove?

$$\mathcal{O}(n)$$

Vector Big O Summary

	Worst	Average
Get	$\mathcal{O}(1)$	$\mathcal{O}(1)$
Add	$\mathcal{O}(n)$	$\mathcal{O}(1)$
Remove	$\mathcal{O}(n)$	$\mathcal{O}(n)$


END OF
FLASHBACK
nick

Your job: Architect of Queue

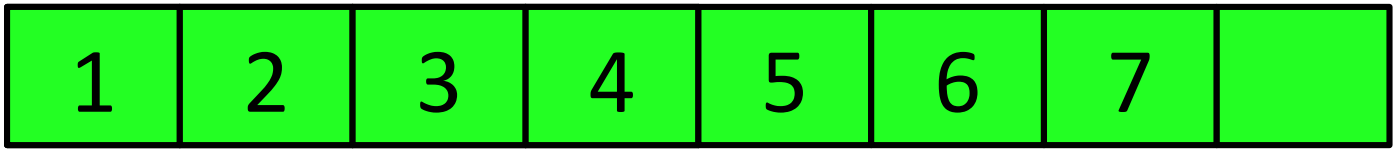
Easiest solution…

```
class QueueInt {            // in QueueInt.h
public:
    QueueInt ();            // constructor

    void enqueue(int value); // append a value
    int dequeue();            // return the first-in value

private:
    VectorInt data;      // member variables
};
```

Excuse Me, Coming Through



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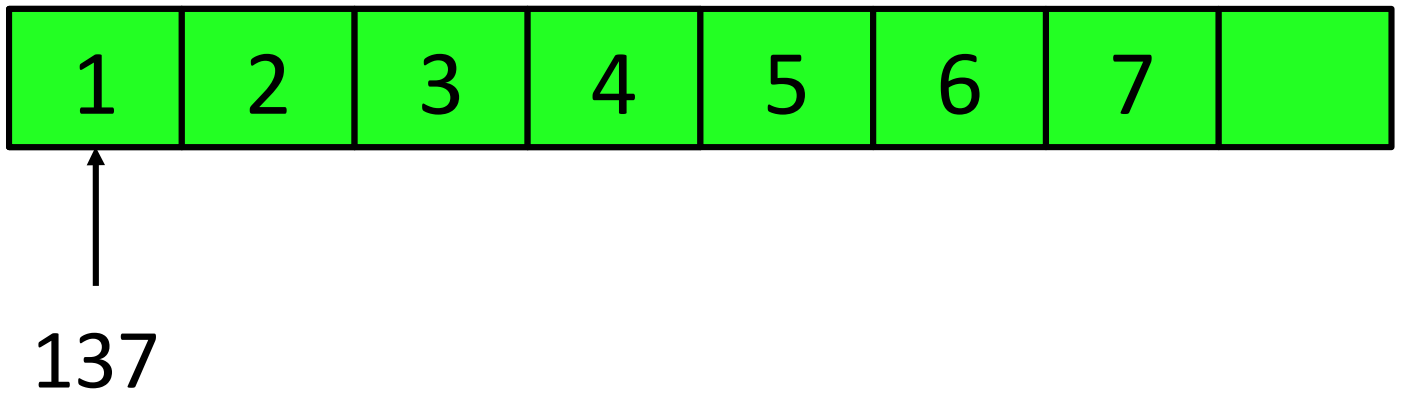

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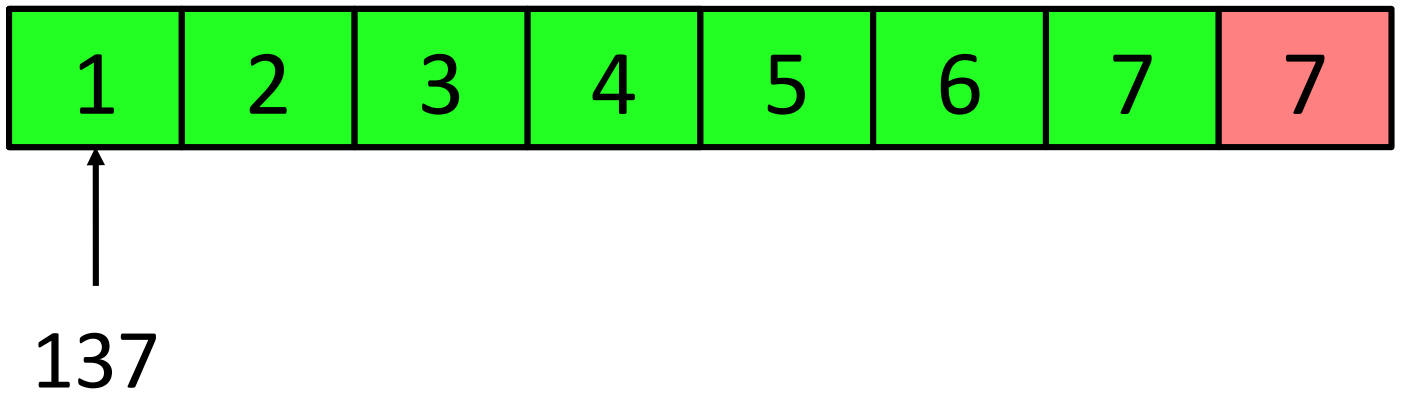

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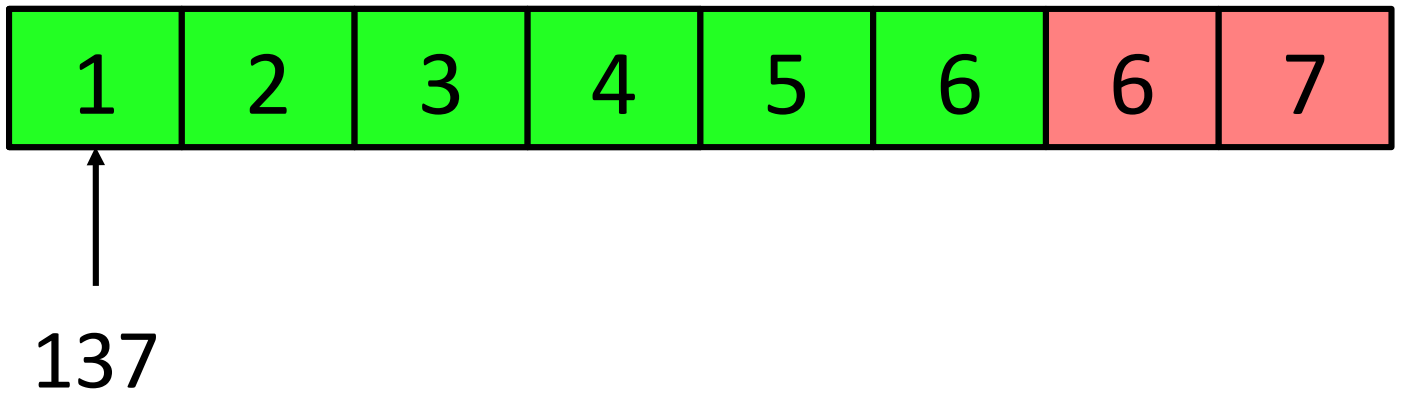

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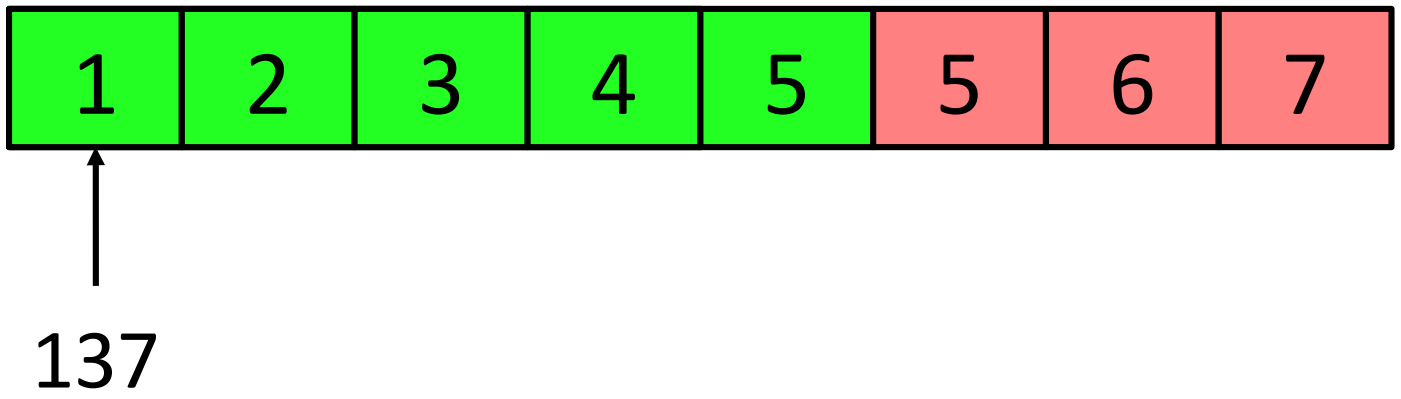

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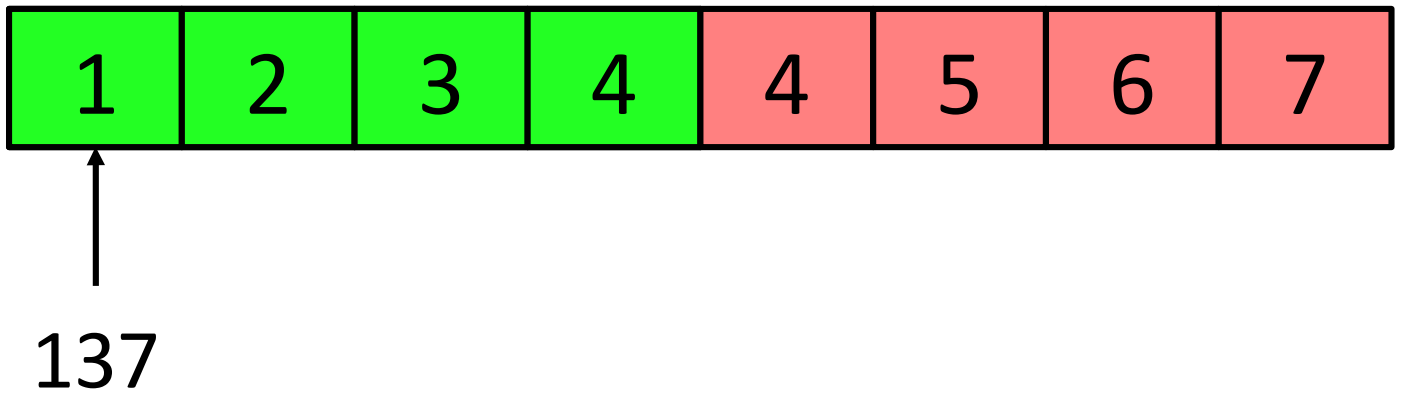

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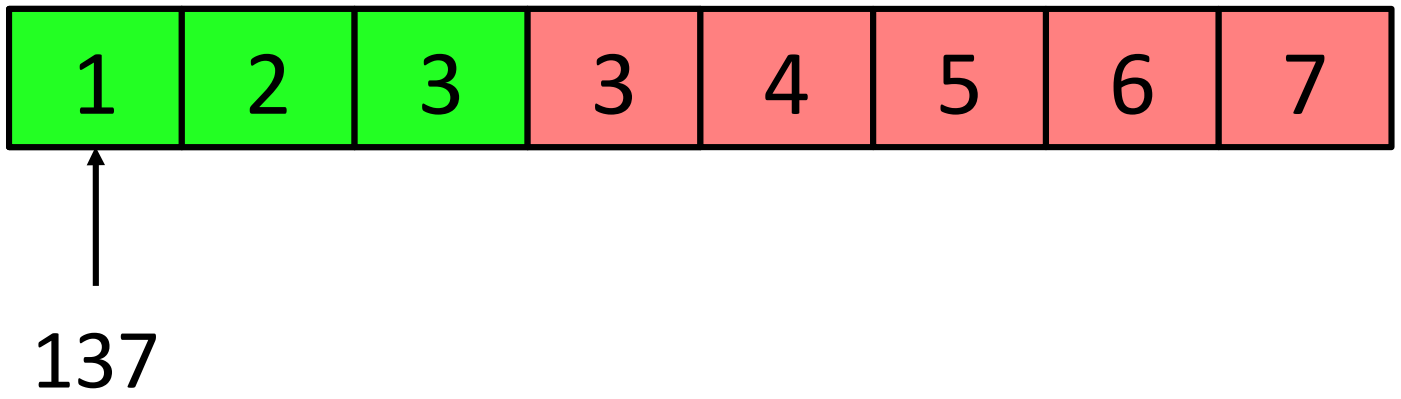

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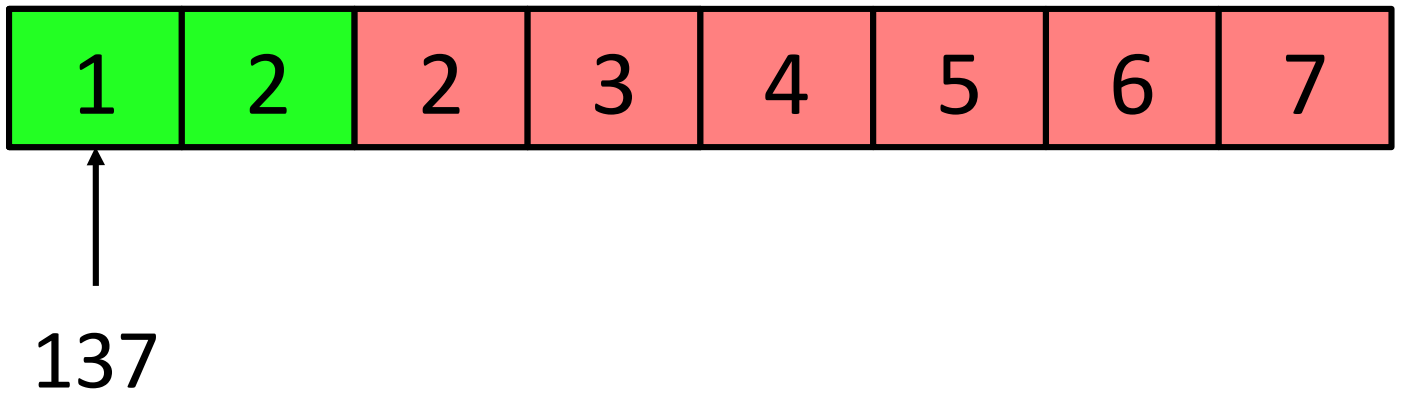

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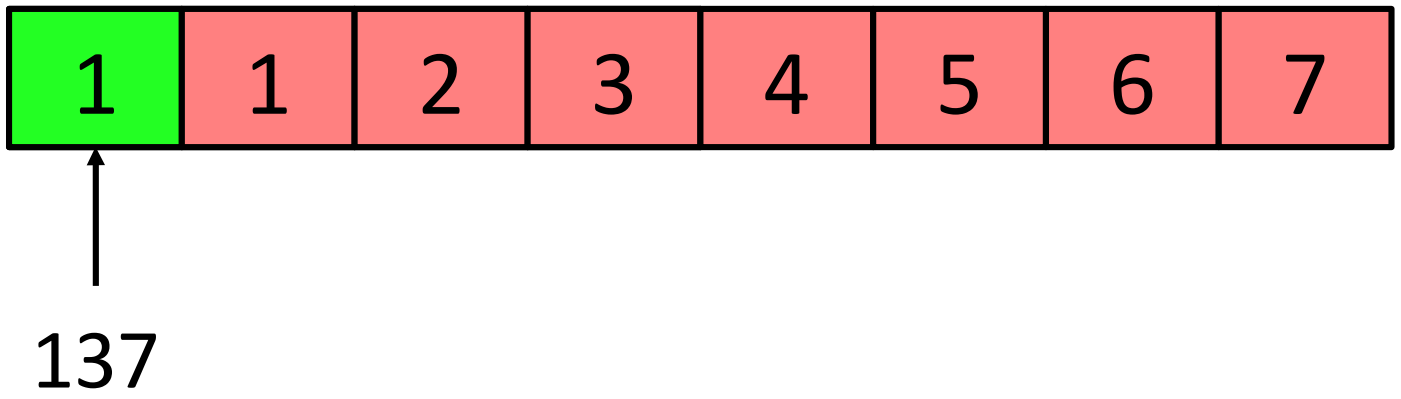
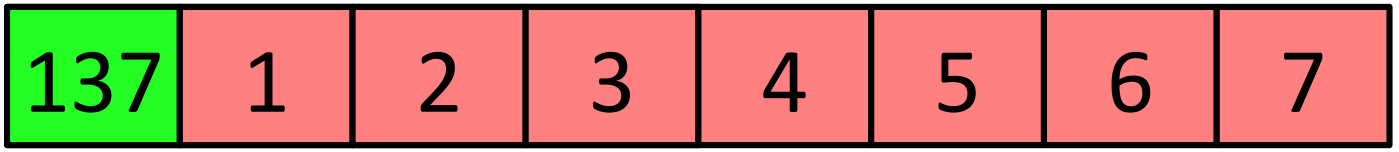


Excuse Me, Coming Through



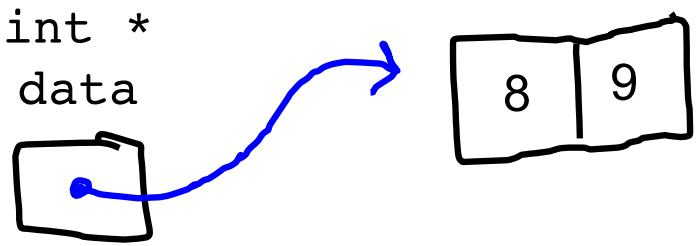
Queue as Vector: Big O

Enqueue	$\mathcal{O}(n)$
Dequeue	$\mathcal{O}(1)$

There’s always a better way

What About This?

```
enqueue(7);
```



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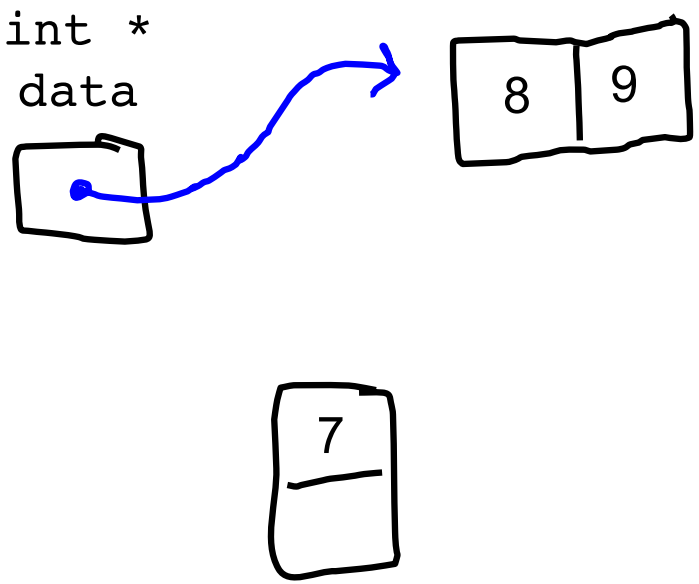

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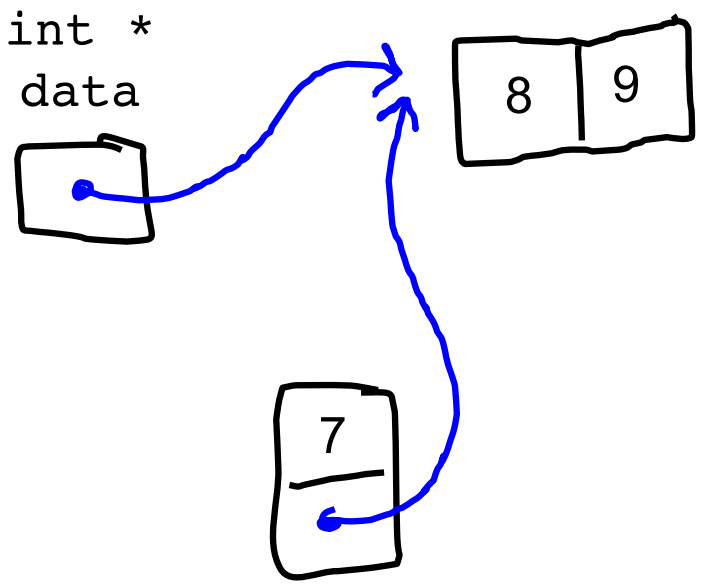

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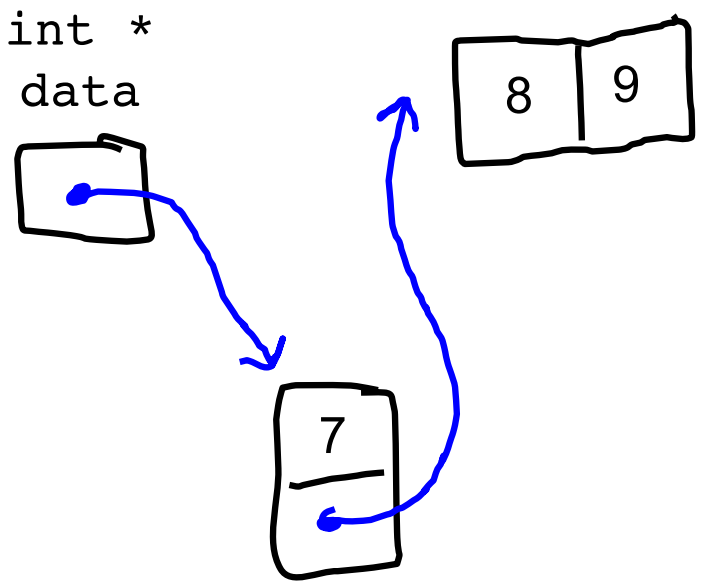

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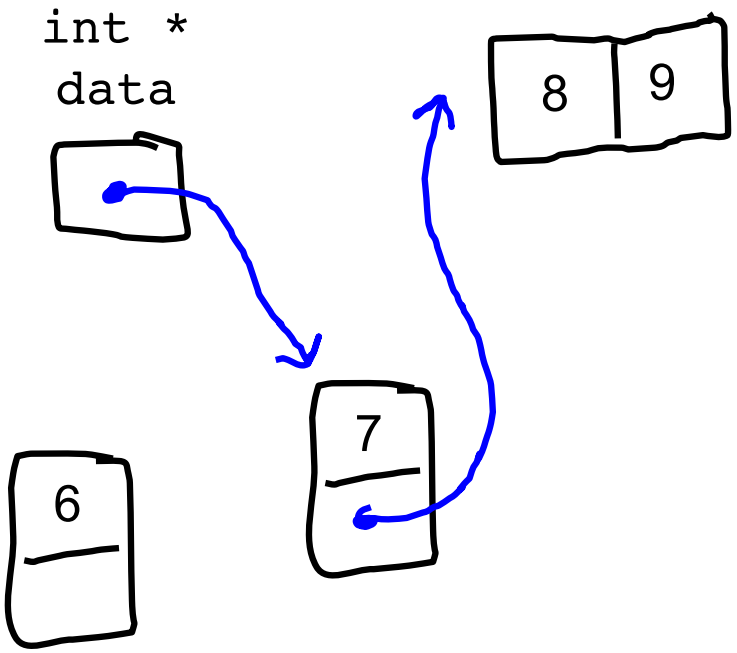

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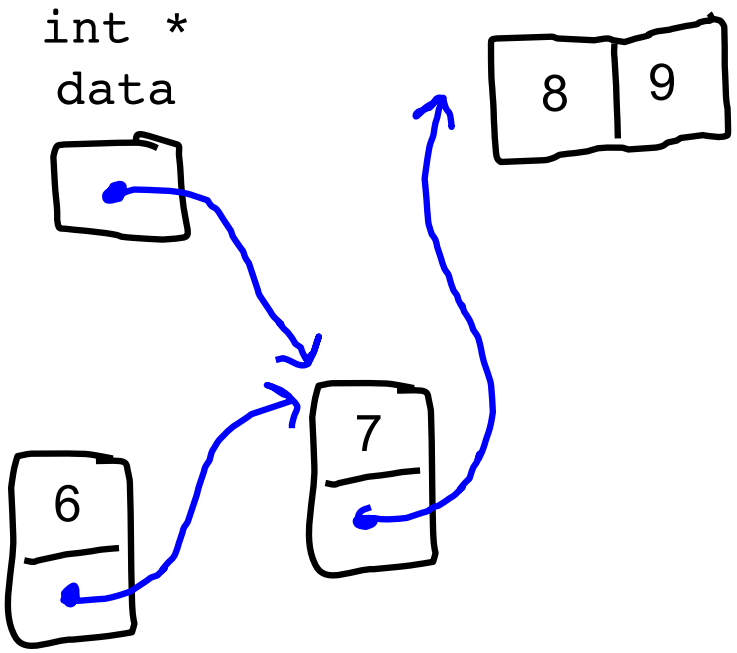

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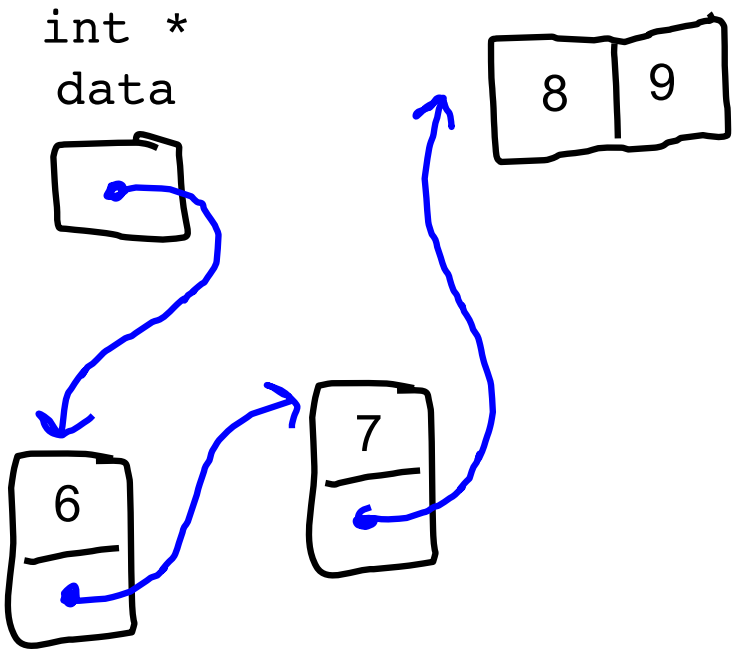

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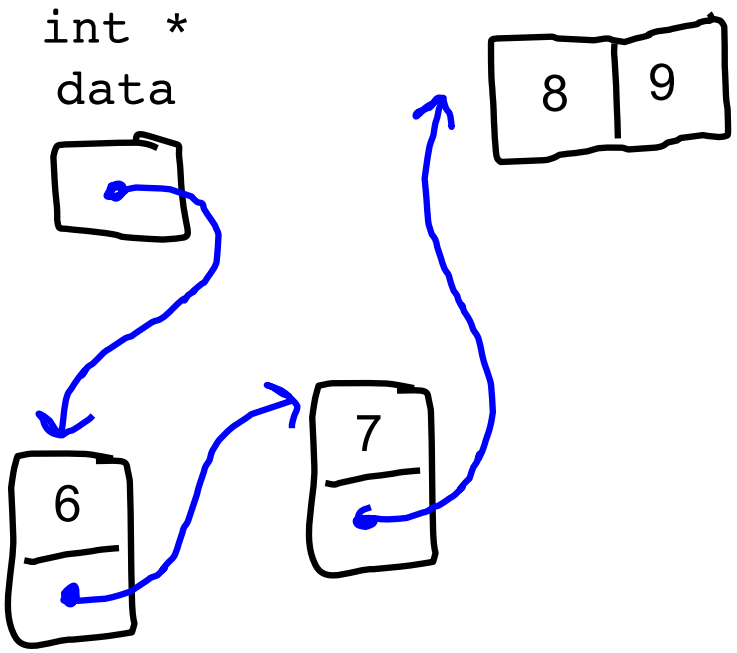
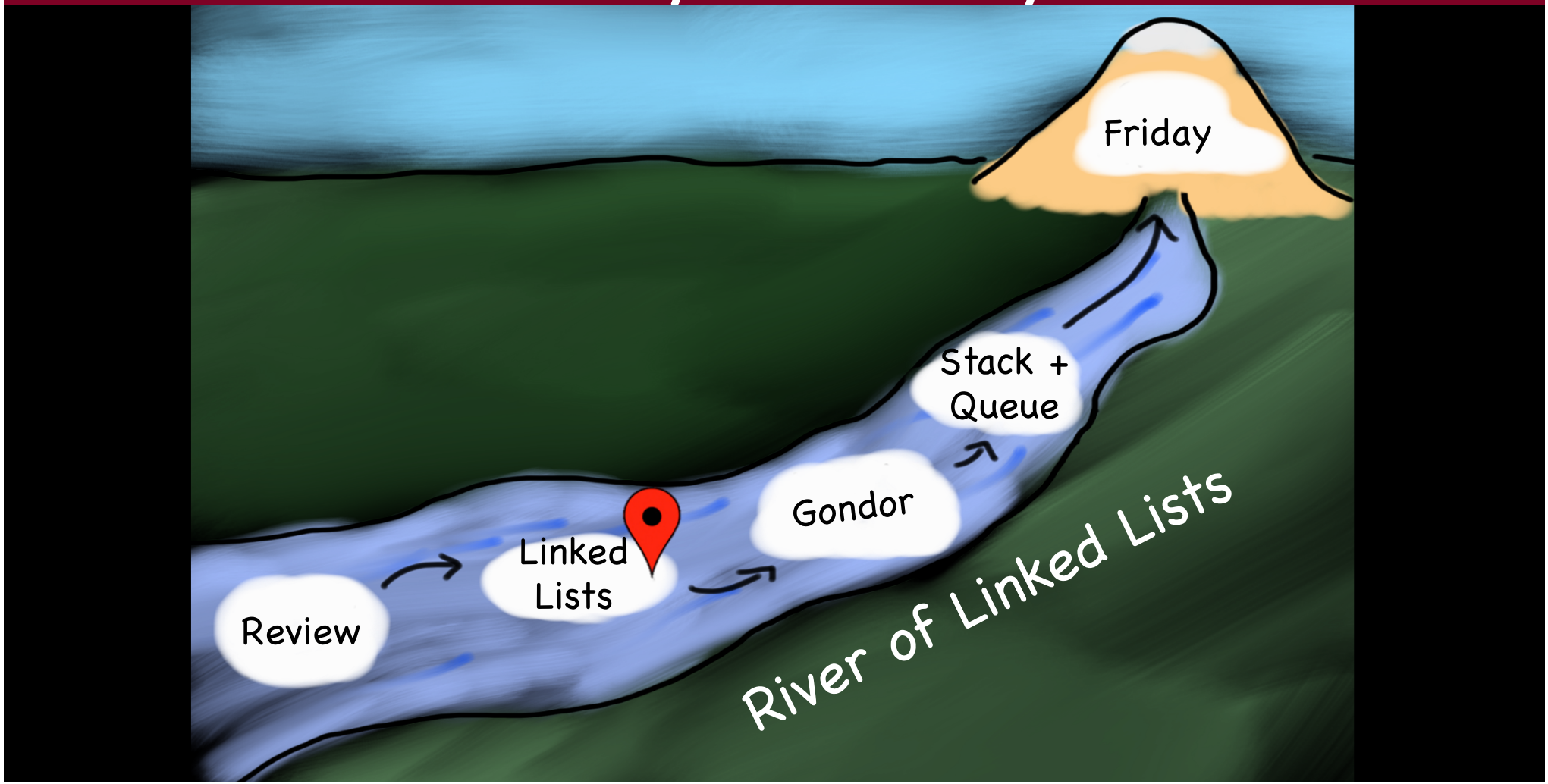
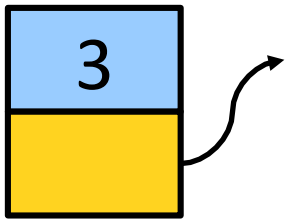


Today's Journey



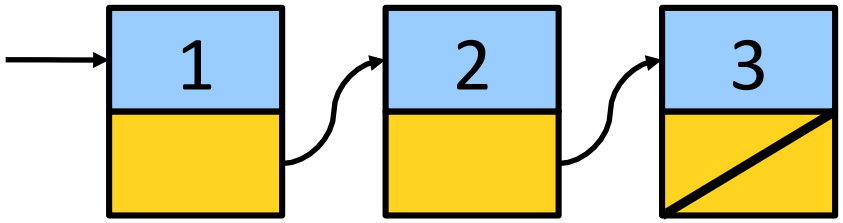
Linked List

- A linked list is a chain of **nodes**.
- Each node contains two pieces of information:
  - Some piece of data that is stored in the sequence
  - A **link** to the next node in the list.
- We can traverse the list by starting at the first cell and repeatedly following its link.



Linked Lists

- A **linked list** is a data structure for storing a sequence of elements.
- Each element is stored separately from the rest.
- The elements are then chained together into a sequence.



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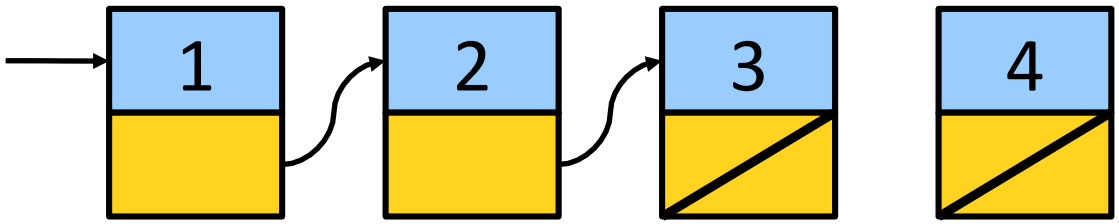

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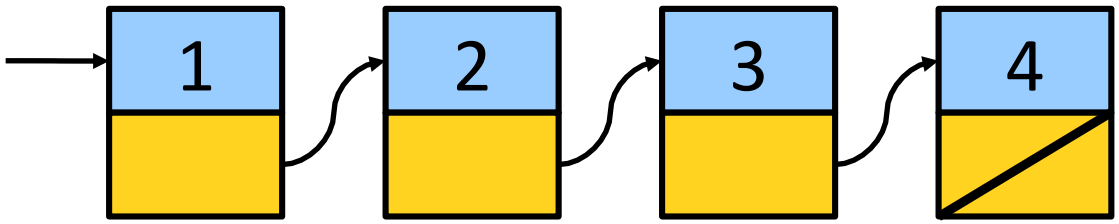

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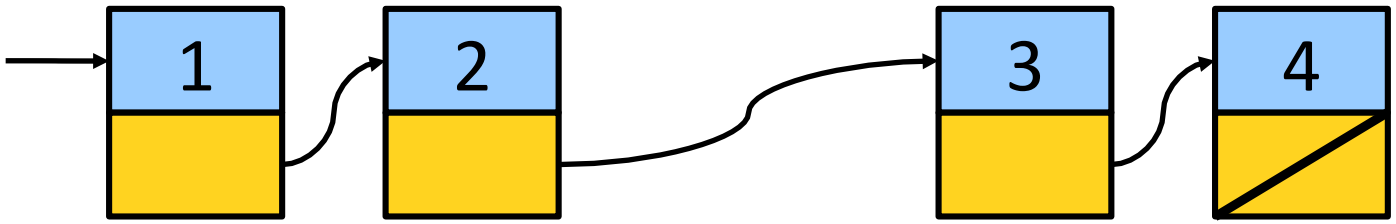

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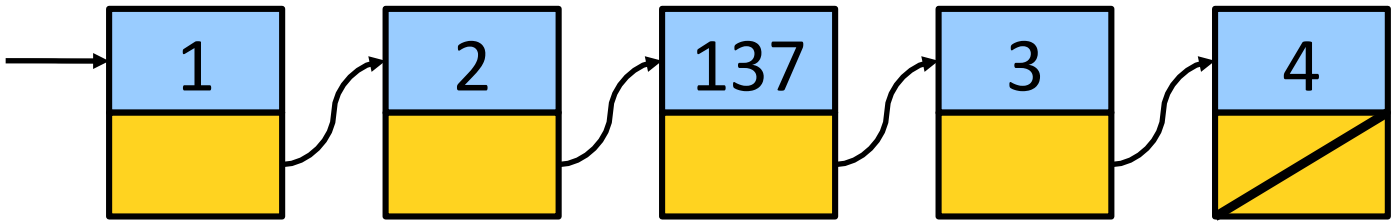

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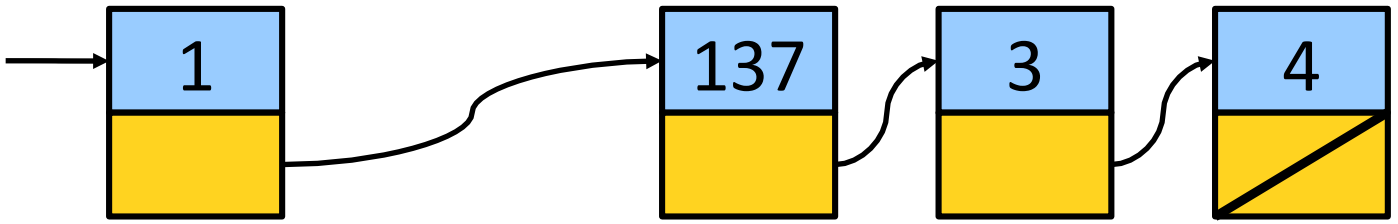

Why Linked Lists?

- Can efficiently splice new elements into the list or remove existing elements anywhere in the list.
- Never have to do a massive copy step;
- Has some tradeoffs; we'll see this later.

Linked List Structure

- For simplicity, let's assume we're building a linked list of **`string`**s.
- We can represent a node in the linked list as a structure:

```
struct Node {
    string value;
    /* ? */ next;
};
```

Linked List of Strings

- For simplicity, let's assume we're building a linked list of **`string`**s.
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struct Node {
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Linked List of Strings

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- We can represent a node in the linked list as a structure:

```
struct Node {
    string value;
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};
```

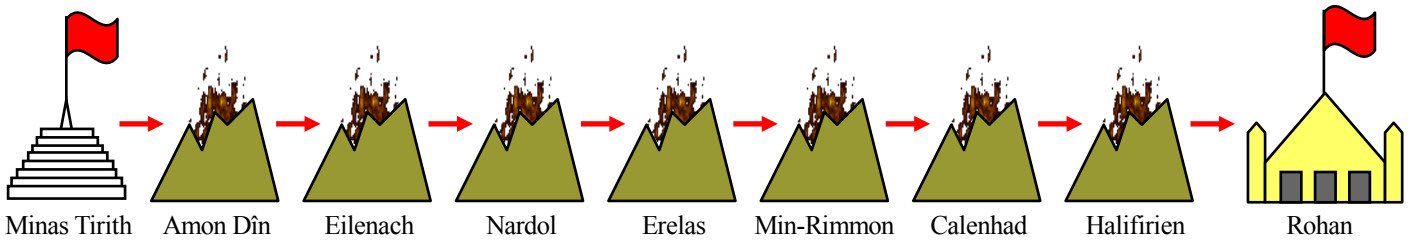
- **The structure is defined recursively!**

First Rule of Linked List Club

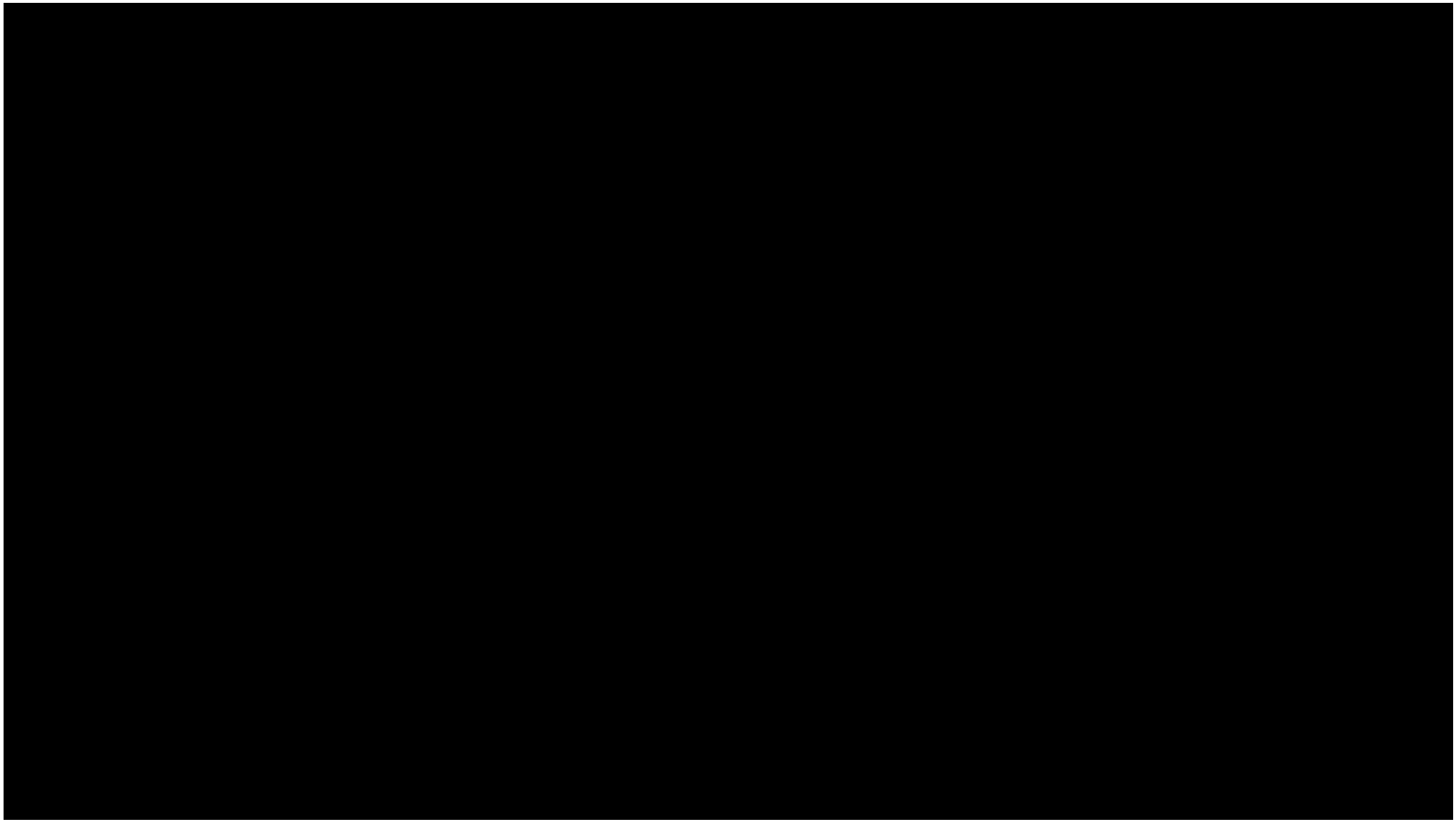
Draw a picture

Lord of the Linked Lists

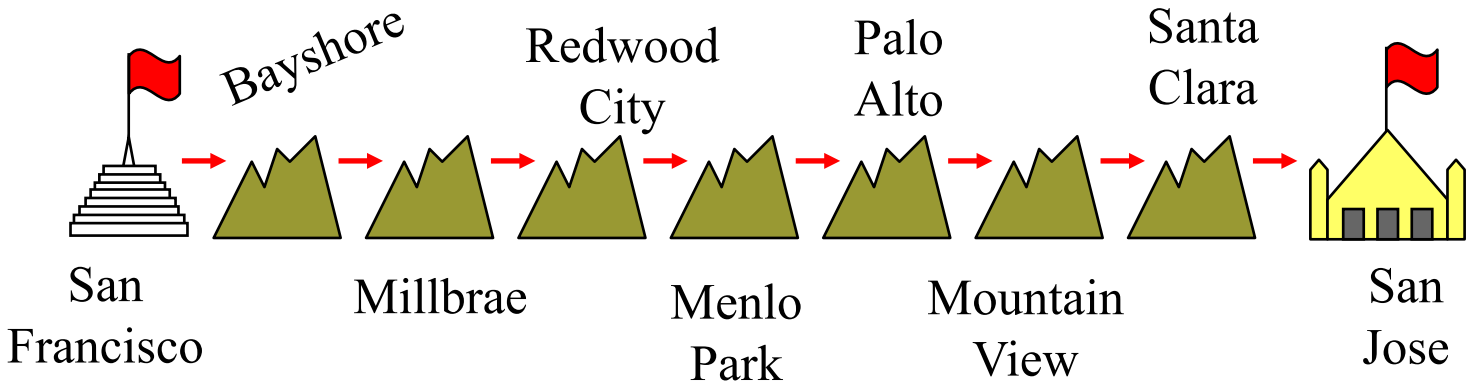
In a scene that was brilliantly captured in Peter Jackson's film adaptation of *The Return of the King,* Rohan is alerted to the danger to Gondor by a succession of signal fires moving from mountain top to mountain top. This scene is a perfect illustration of the idea of message passing in a linked list.




THE
LORD OF THE RINGS
THE RETURN OF THE KING



Step 1: Make this linked list



Step 2: Light the fires….

```
Lighting the fire of San Francisco!
```

Lord of the Linked Lists

```
struct Tower {
   string name;   /* The name of this tower    */
   Tower *link;   /* Pointer to the next tower */
};
```

```
// add the first tower
Tower * head = new Tower;
head->name = “San Jose”;
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```
Tower *createTower(string name, Tower *link) {
    Tower *tp = new Tower;
    tp->name = name;
    tp->link = link;
    return tp;
}
```

Linked List Trace

```
// main
Tower * head = new Tower;
head->name = "San Jose";
head->link = NULL;

head = createTower("Santa Clara", head);
head = createTower("Mountain View", head);
head = createTower("Palo Alto", head);
head = createTower("Menlo Park", head);
head = createTower("Redwood City", head);
head = createTower("Millbrae", head);
head = createTower("Bayshore", head);
head = createTower("San Francisco", head);
```

```
struct Tower{
    string name;
    Tower * link;
};
```

```
Tower *createTower(string name, Tower *link) {
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```

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```

```
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    Tower * link;
};
```

```
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    Tower *tp = new Tower;
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Linked List Trace

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head = createTower("San Francisco", head);
```

```
struct Tower{
    string name;
    Tower * link;
};
```

```
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    tp->name = name;
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}
```

Linked List Trace

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```

Linked List Trace

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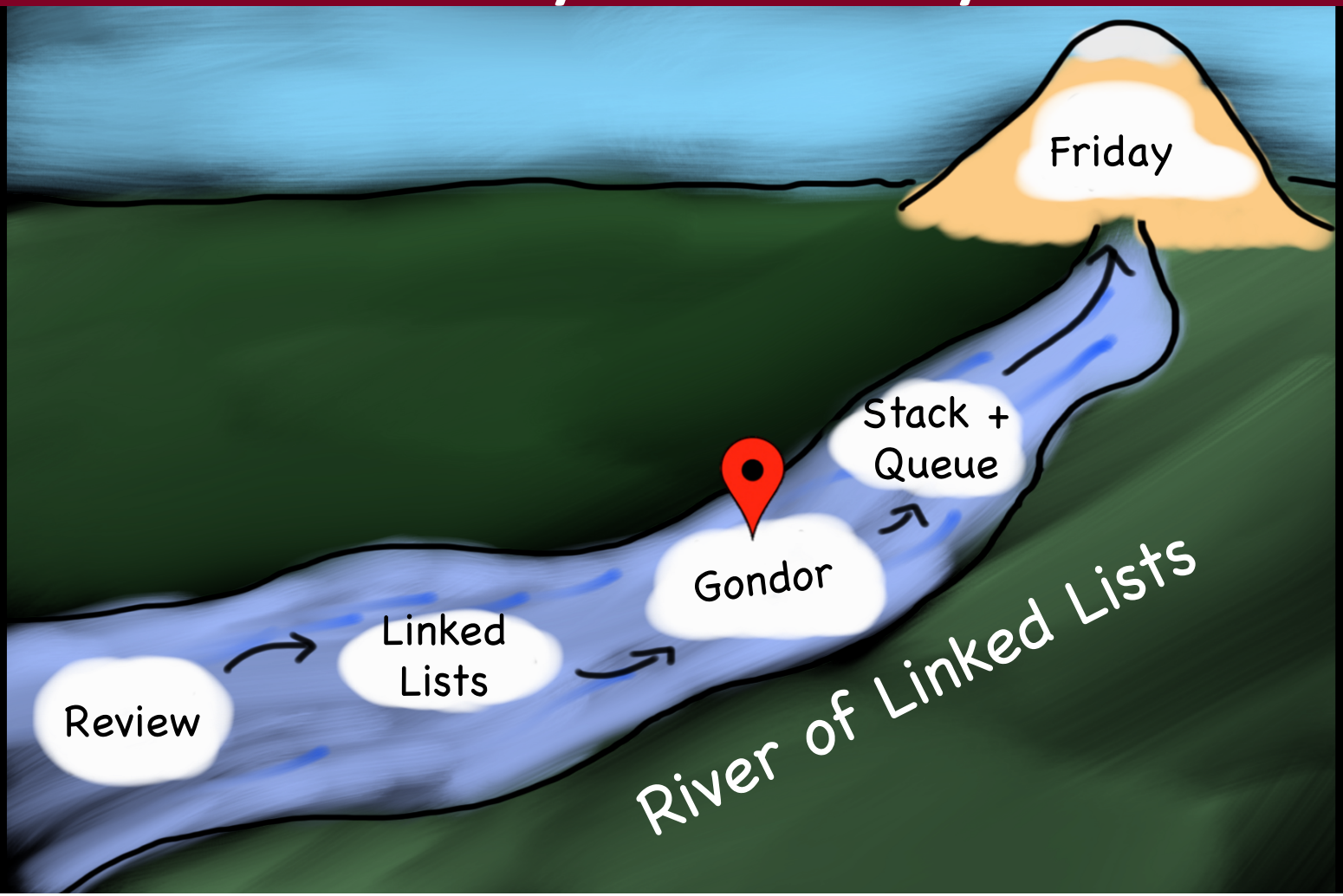
```
struct Tower{
    string name;
    Tower * link;
};
```

```
Tower *createTower(string name, Tower *link) {
    Tower *tp = new Tower;
    tp->name = name;
    tp->link = link;
    return tp;
}
```

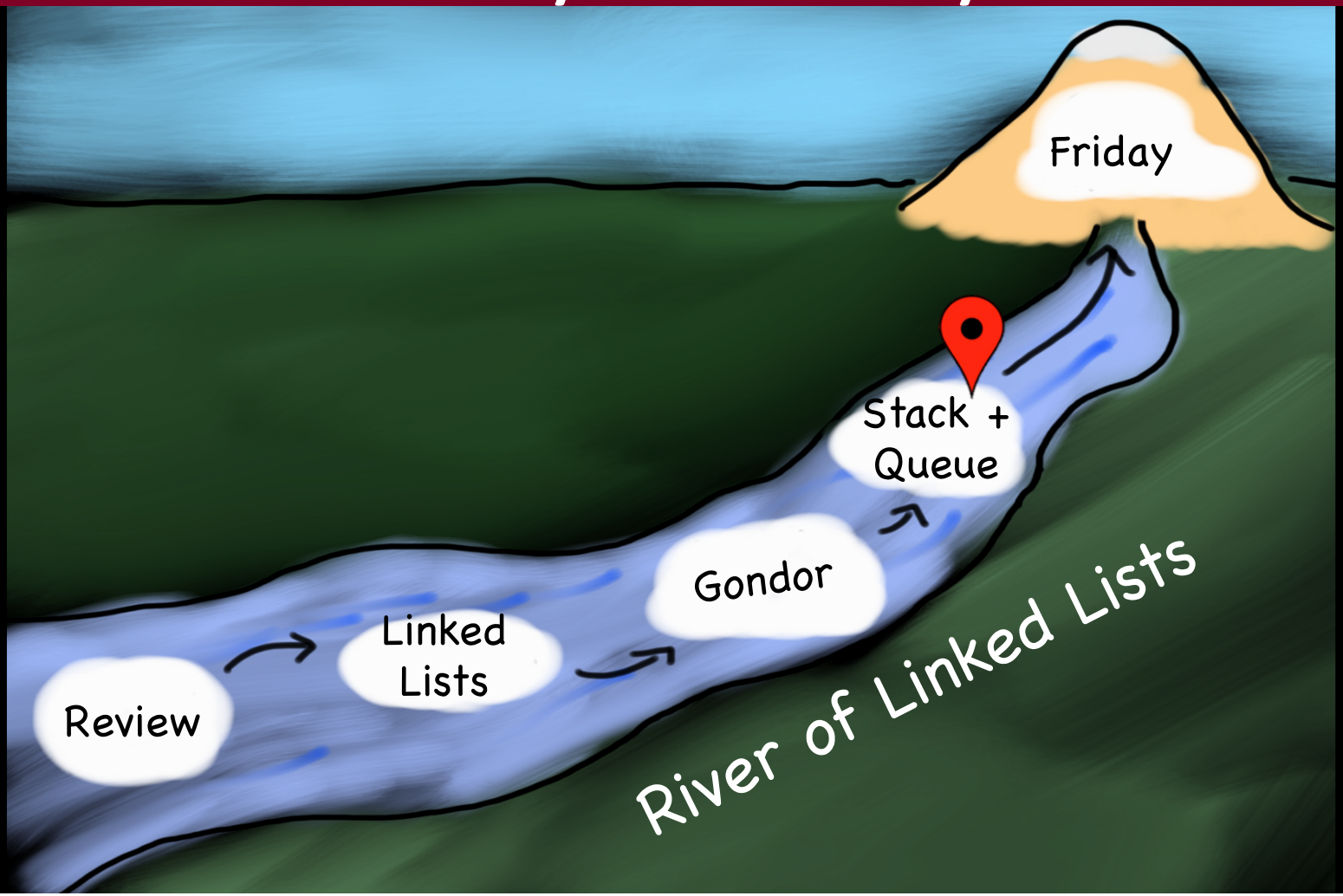
```
void signal(Tower *start) {
    if (start != NULL) {
        cout << "Lighting " << start->name << endl;
        signal(start->link);
    }
}
```

```
signal(head);
```

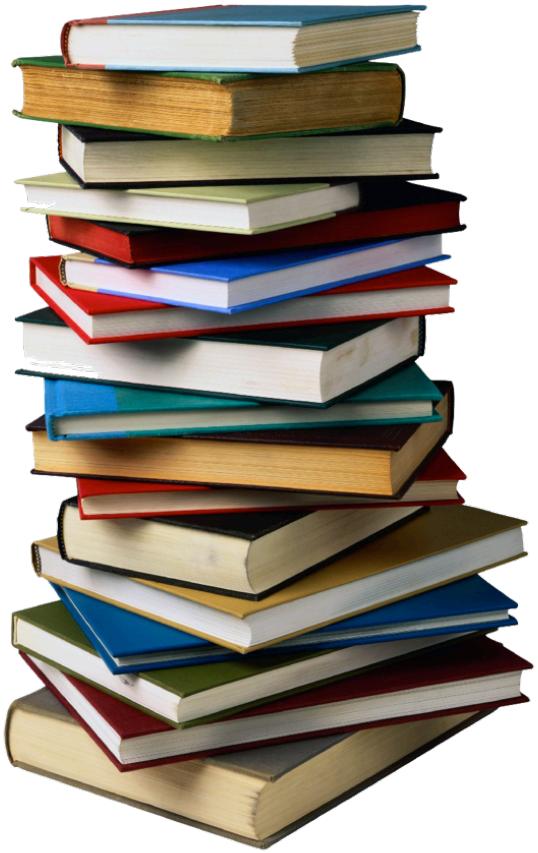
Today's Journey



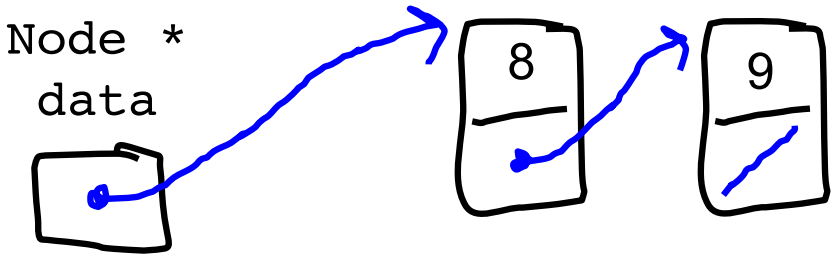
Today's Journey



How is the Stack Implemented?



```
struct Node{
   int value;     /* The value of this elem    */
   Node *link;    /* Pointer to the next node */
};
```


Node *
data
8
9

Stack

```
class StackInt {              // in StackInt.h
public:
    StackInt ();              // constructor

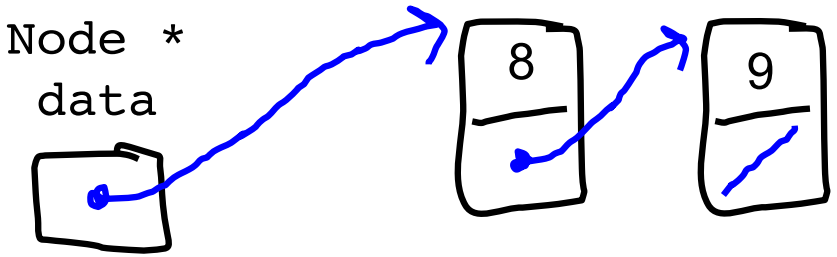
    void push(int value); // append a value
    int pop();                // return the first-in value

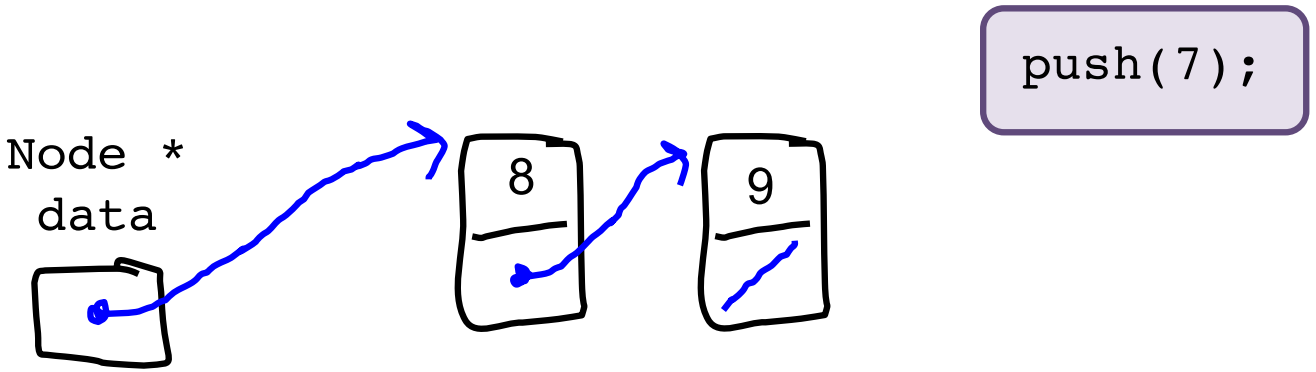
private:
    struct Node {
      int value;
      Node * link;
    };
    Node * data;      // member variables
};
```

Stack Implementation

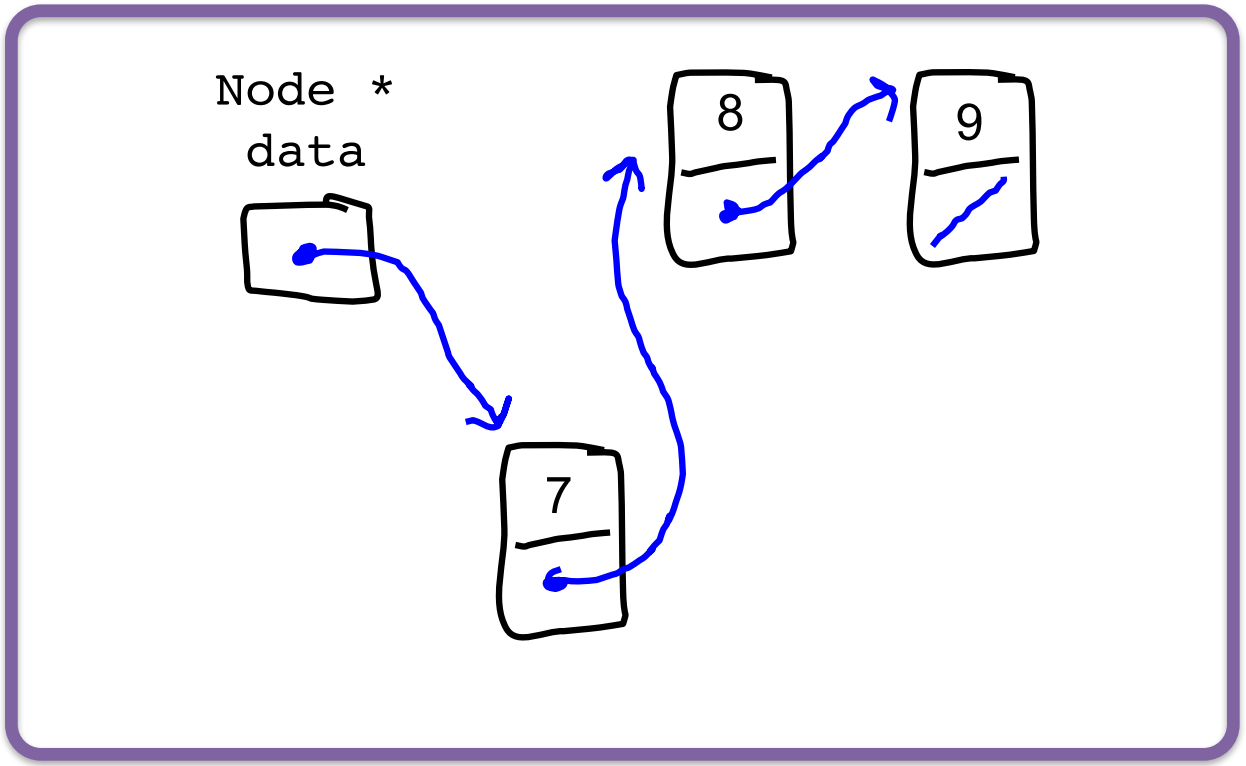
```
void StackInt::push(int v) {
    Node * temp = new Node;
    temp->value = v;
    temp->link = data;
    data = temp;
}

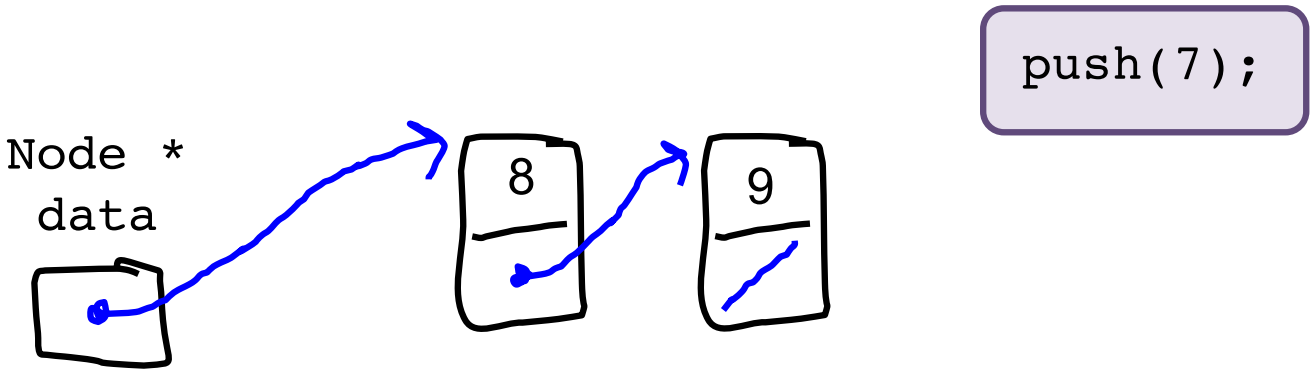
int StackInt::pop() {
    int toReturn = data->value;
    Node * temp = data;
    data = temp->link;
    delete data;
}
```


Node *
data
8
9


Node *
data
8
9
push(7);

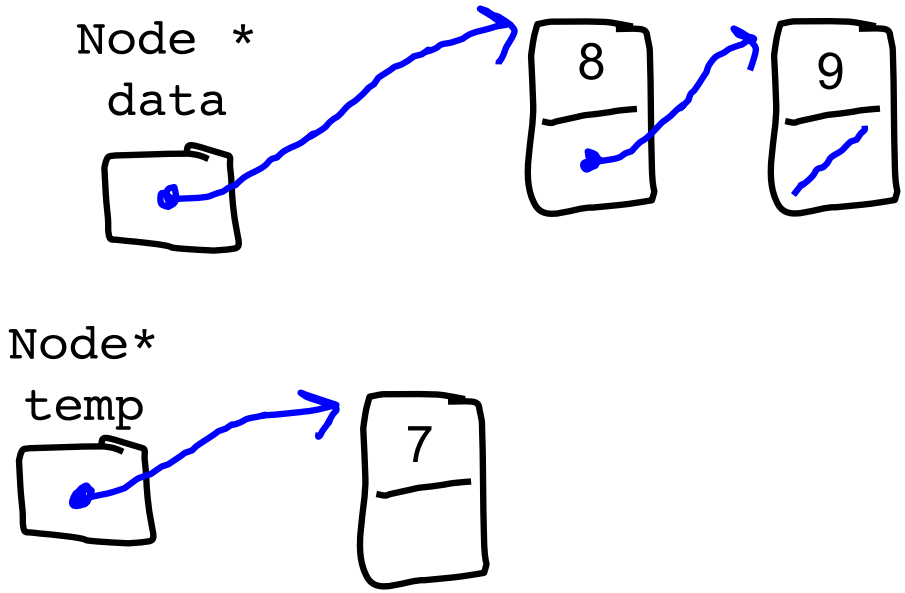
Goal of Push




Node *
data
8
9
push(7);

Stack is a Linked List

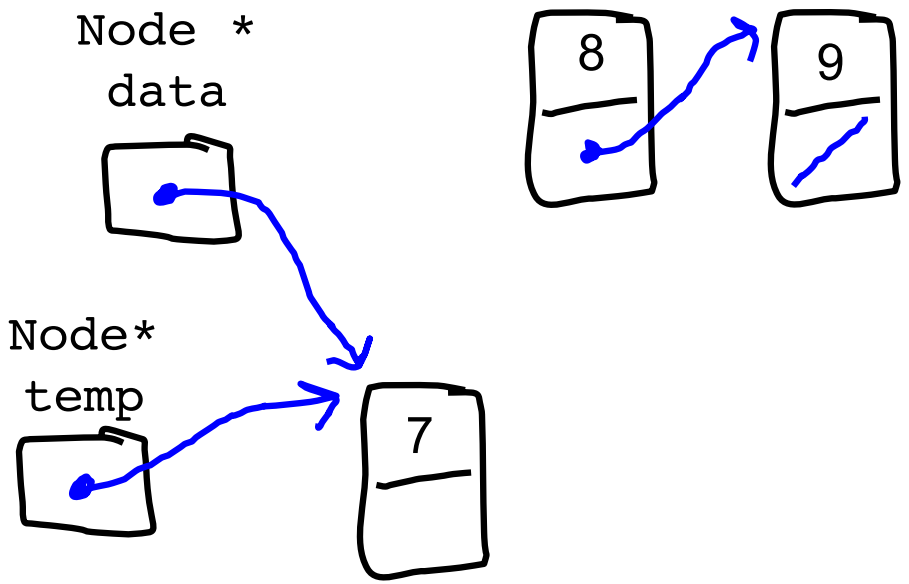
```
push(7);
```



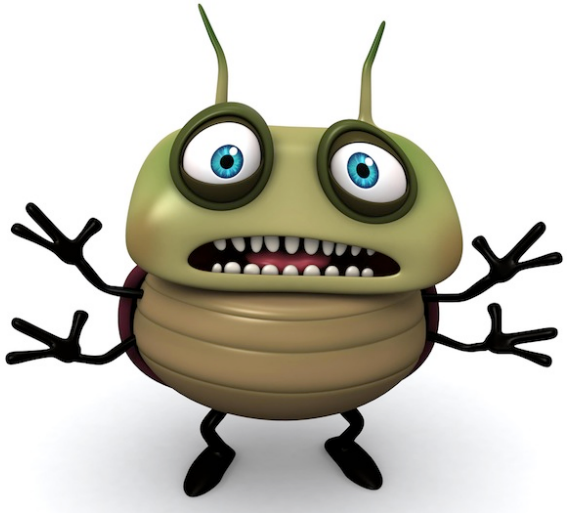

```
Node * temp =  new Node;
temp -> value = 7;
```

Stack is a Linked List

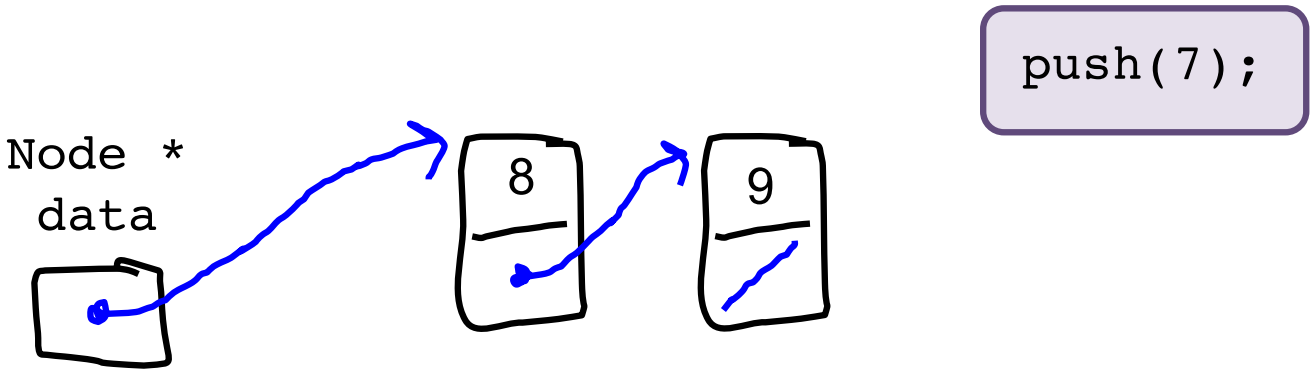
```
push(7);
```



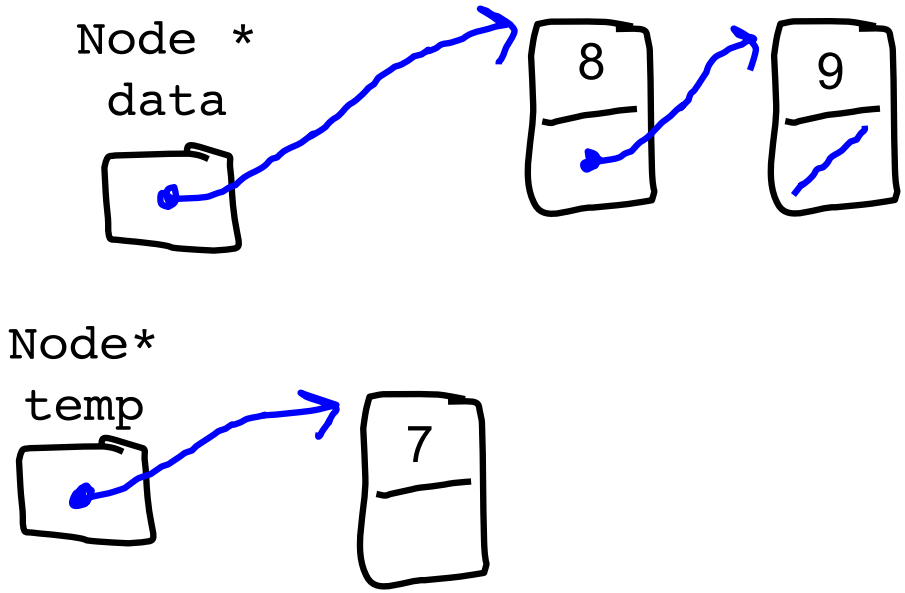

```
data = temp;
```



BRAAWWRRRR!

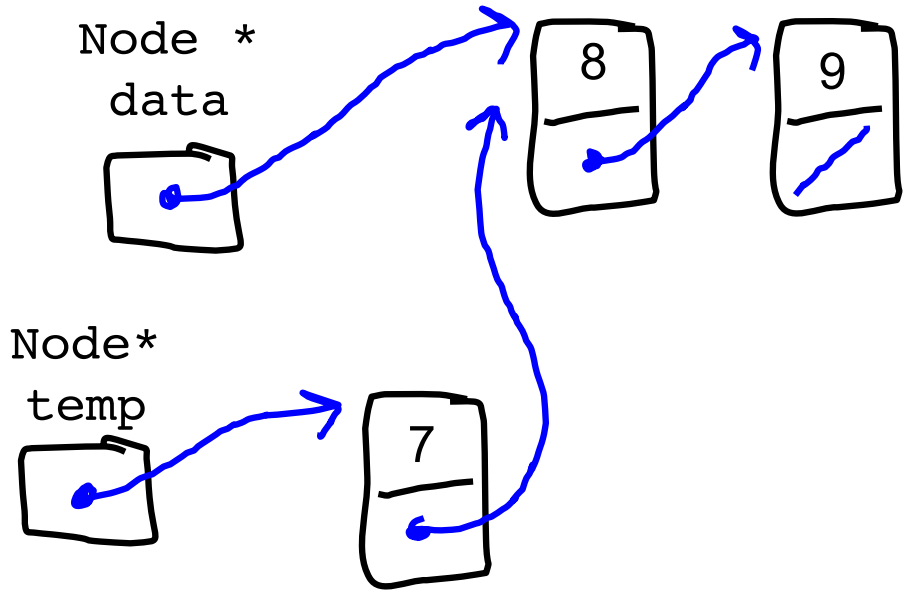

Node *
data
8
9
push(7);

```
push(7);
```



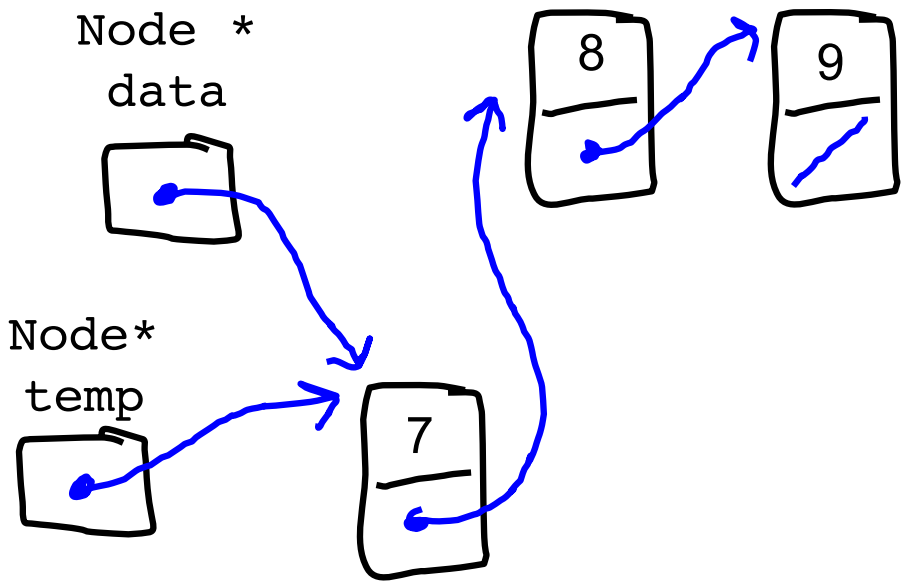

```
Node * temp =  new Node;
temp -> value = 7;
```

```
push(7);
```



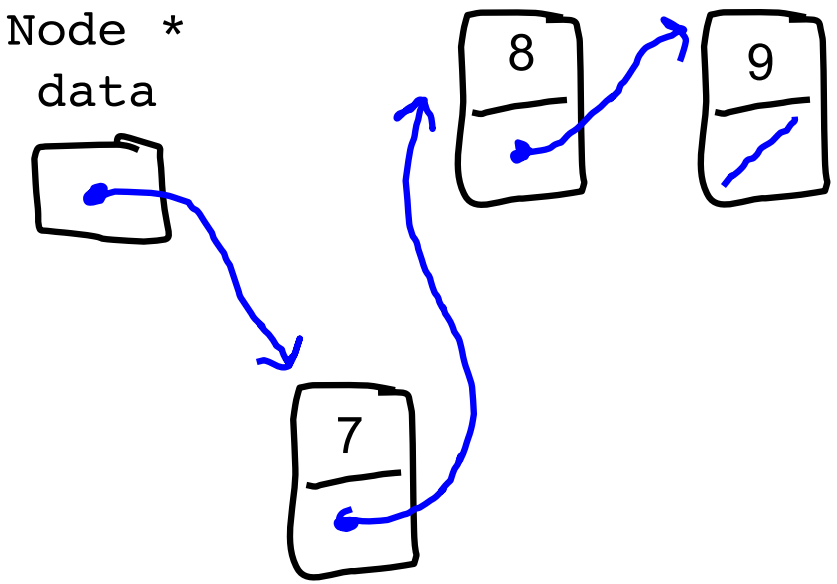

```
temp -> link = data;
```

```
push(7);
```

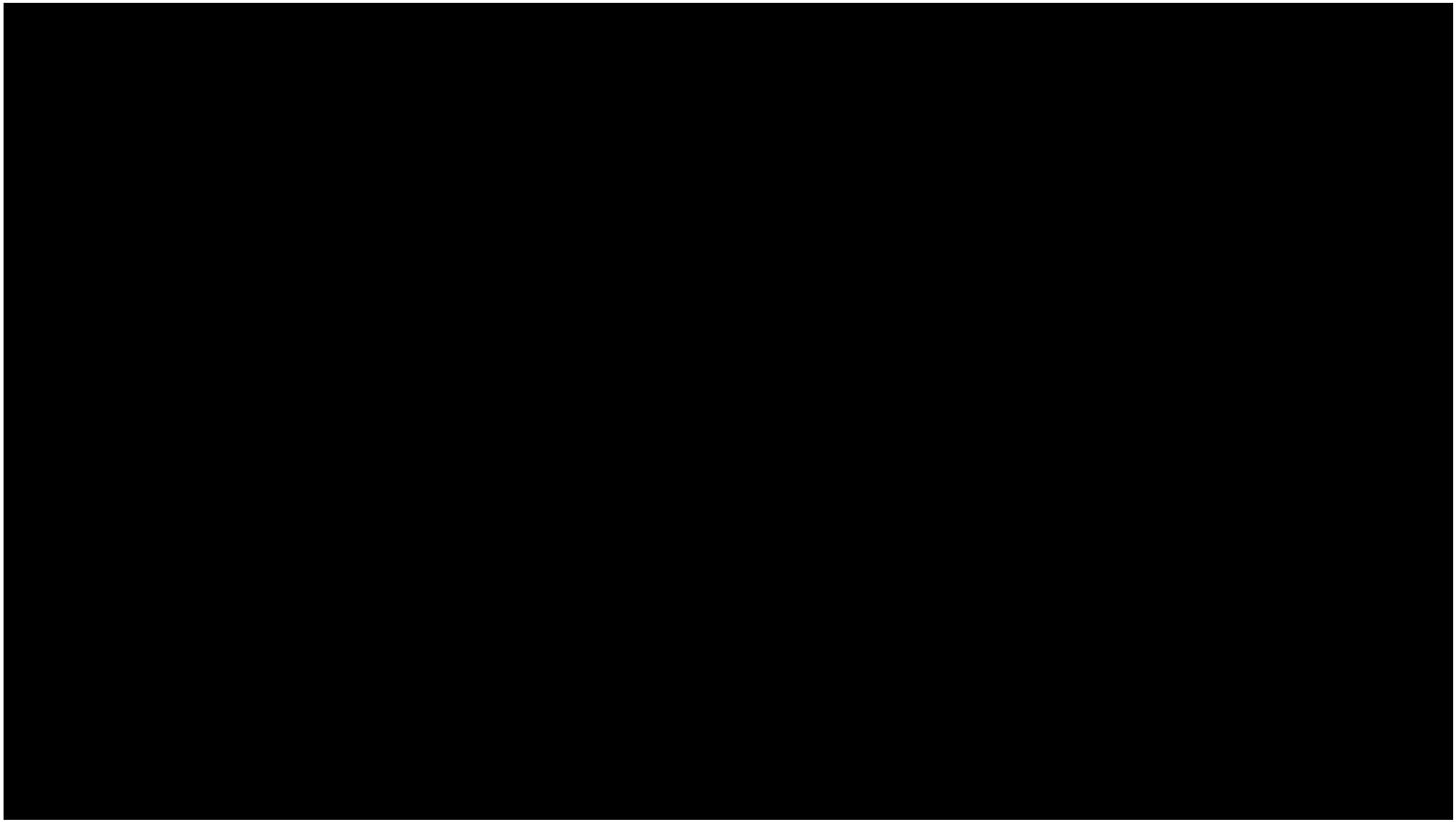



```
data = temp;
```

```
push(7);
```

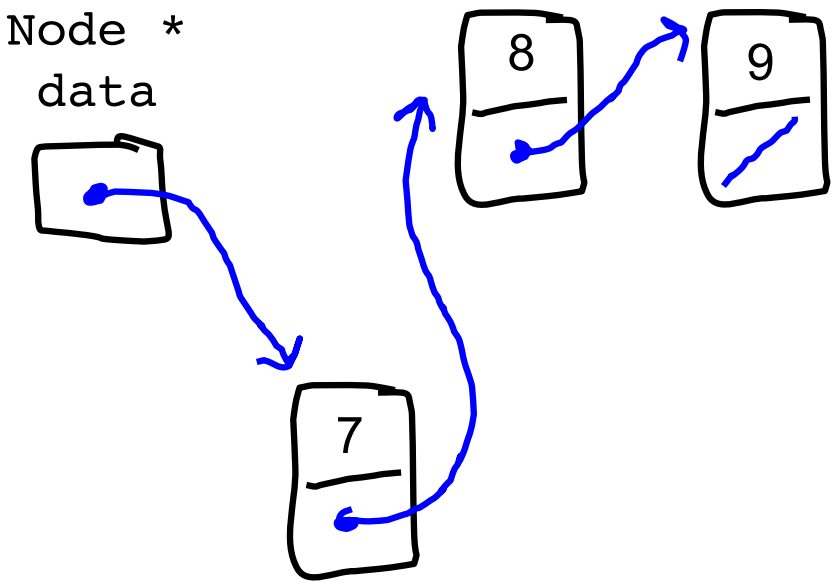


exit function

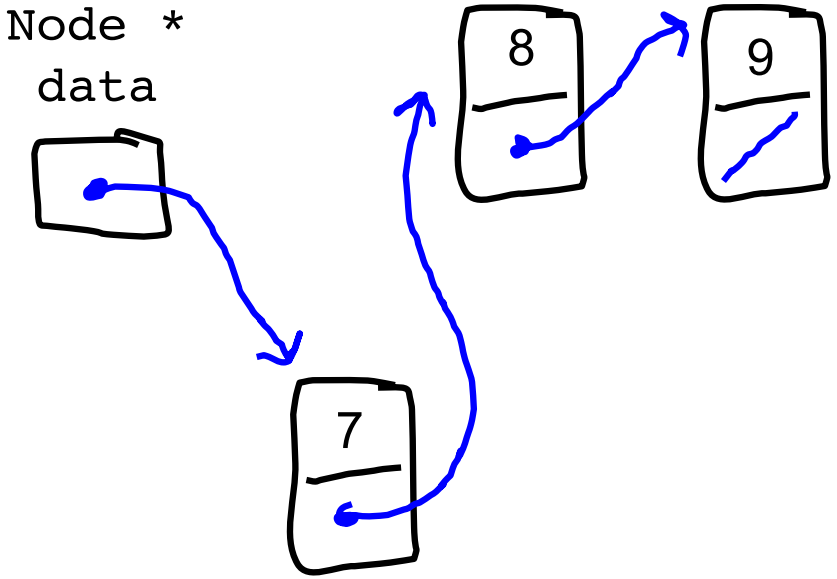


Stack is a Linked List

```
pop();
```



Stack is a Linked List



pop();

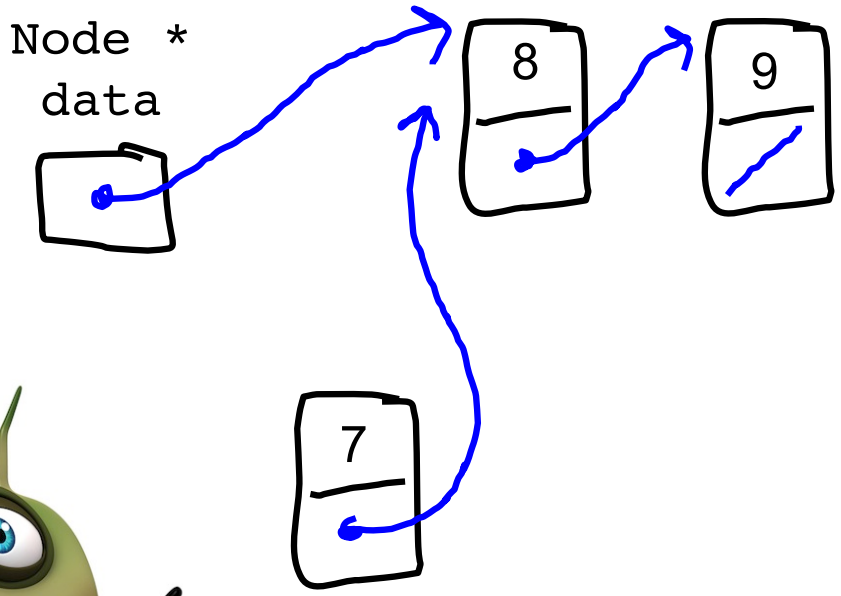
int toReturn

7

```
int toReturn = data->value;
```

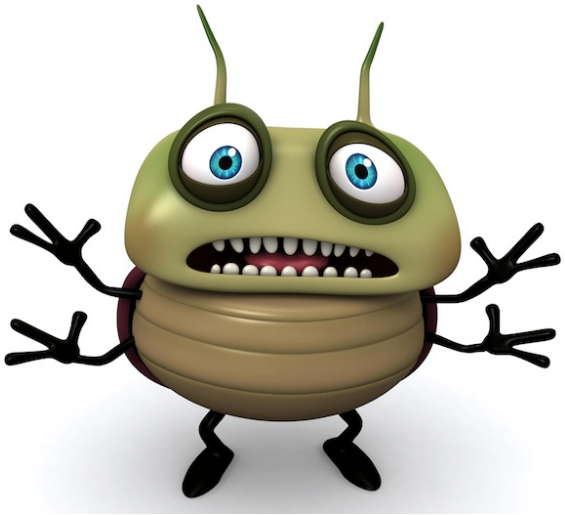
Stack is a Linked List

```
pop();
```




```
int toReturn
```

```
7
```

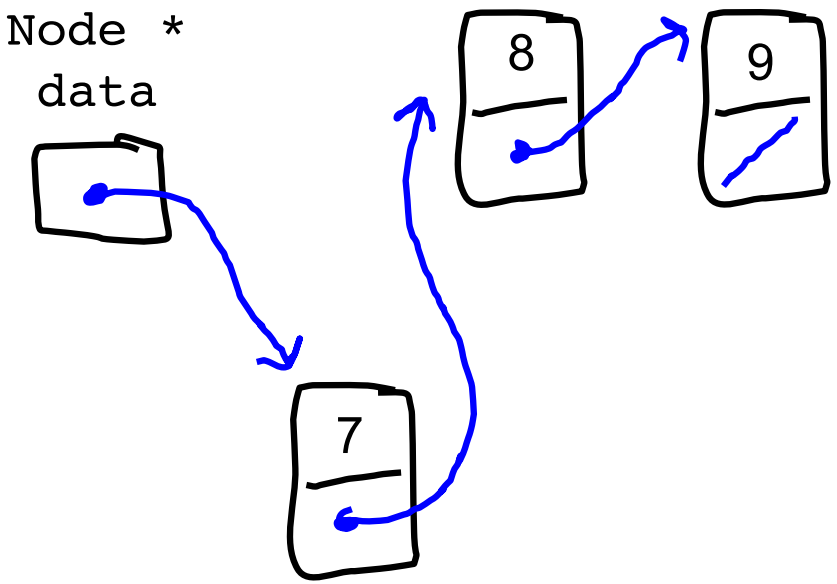


```
data = data->link;
```

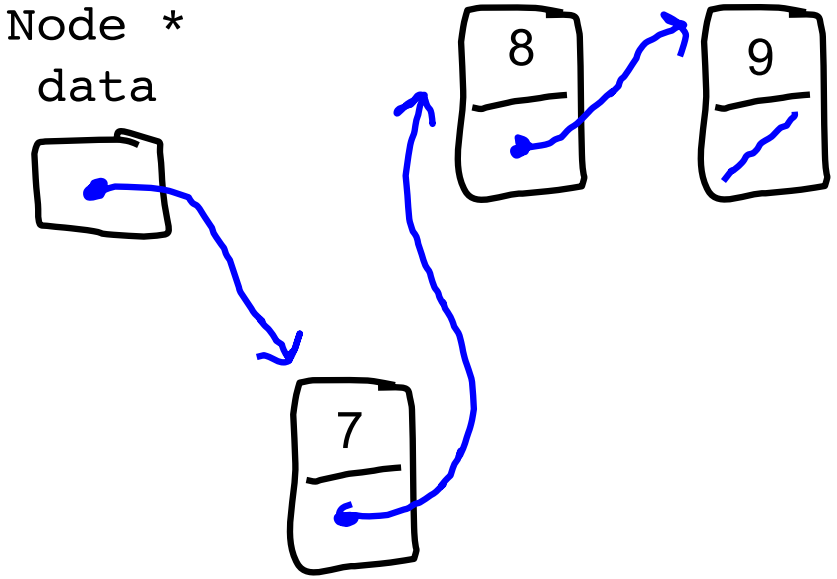
That didn’t work. Let’s try again…

Stack is a Linked List

```
pop();
```



Stack is a Linked List



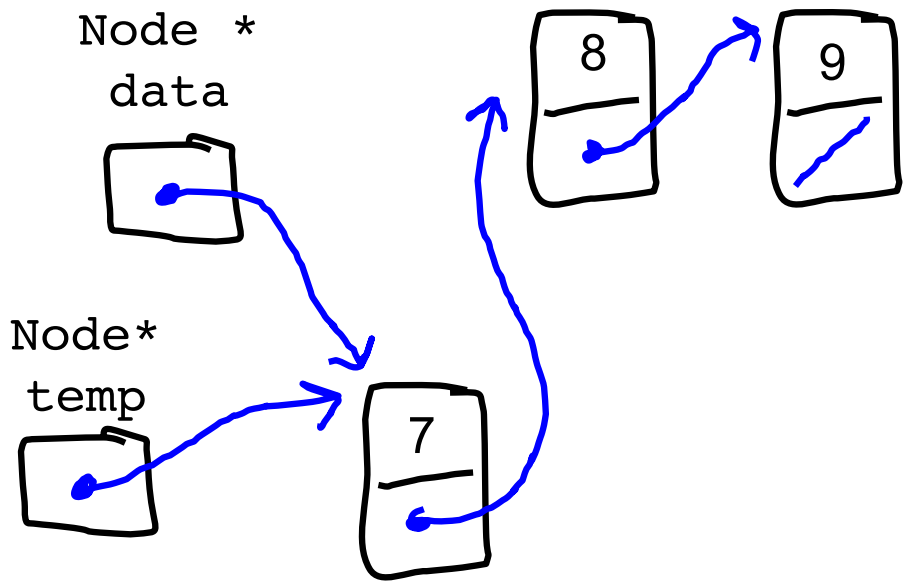
pop();

int toReturn

7

```
int toReturn = data->value;
```

Stack is a Linked List



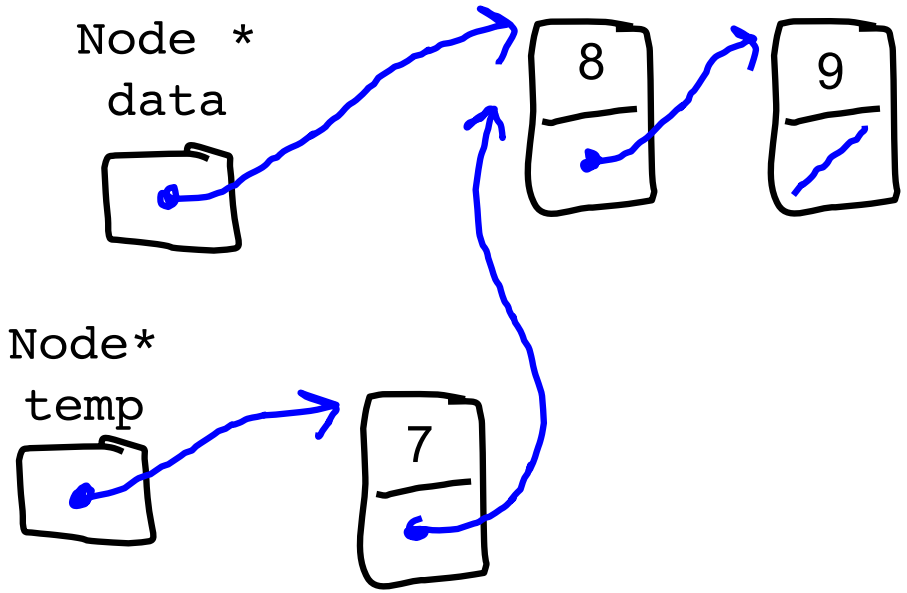

```
pop();
```

```
int toReturn
```

```
7
```

```
Node * temp = data;
```

Stack is a Linked List



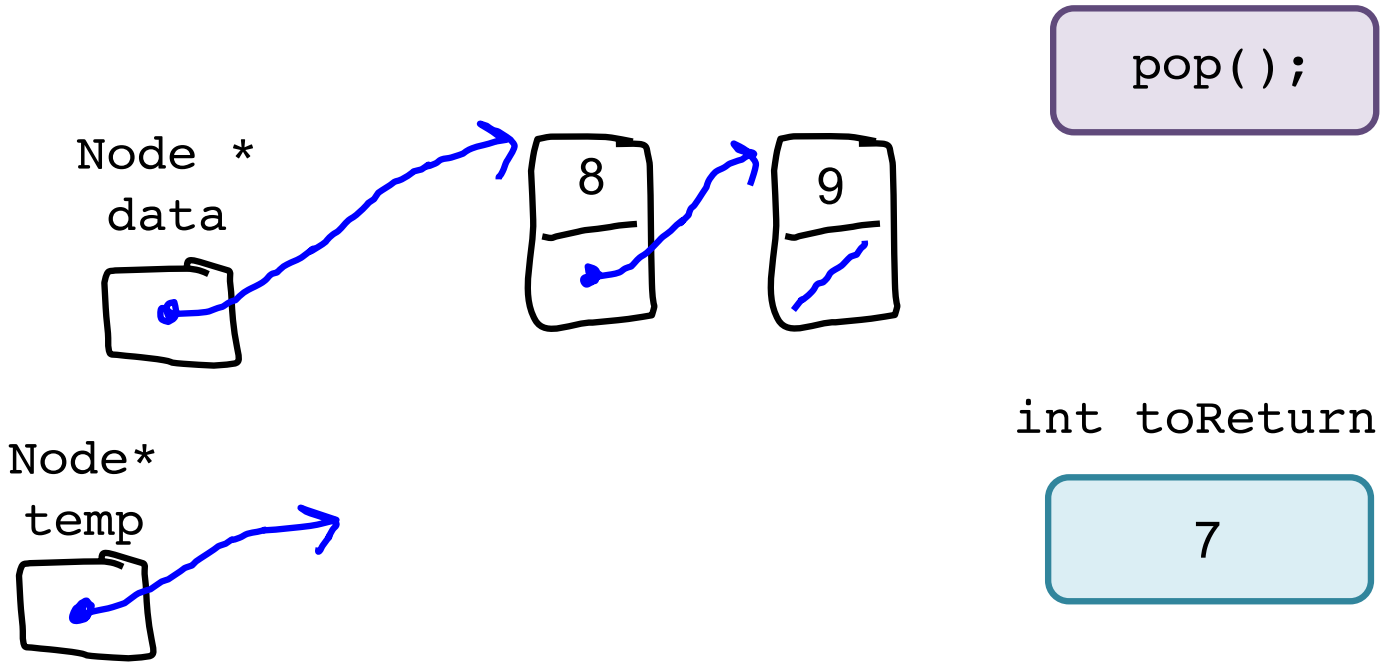

```
pop();
```

```
int toReturn
```

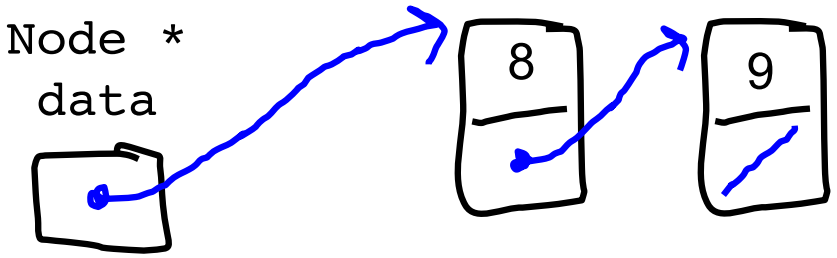
```
7
```

```
data = temp->link;
```

Stack is a Linked List



Stack is a Linked List




```
pop();
```

```
int toReturn
```

7

```
return toReturn;
```

Stack

```
class StackInt {              // in StackInt.h
public:
    StackInt ();              // constructor

    void push(value);          // append a value
    int pop();                // return the first-in value

private:
    struct Node {
      int value;
      Node * link;
    };
    Node * data;      // member variables
};
```

Stack Implementation

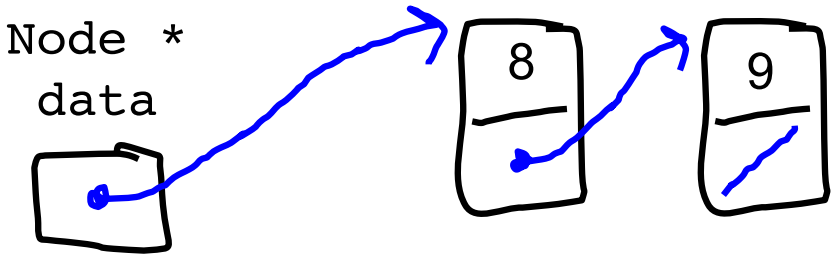
```
void StackInt::push(int v) {
    Node * temp = new Node;
    temp->value = v;
    temp->link = data;
    data = temp;
}

int StackInt::pop() {
    int toReturn = data->value;
    Node * temp = data;
    data = temp->link;
    delete temp;
    return toReturn;
}
```

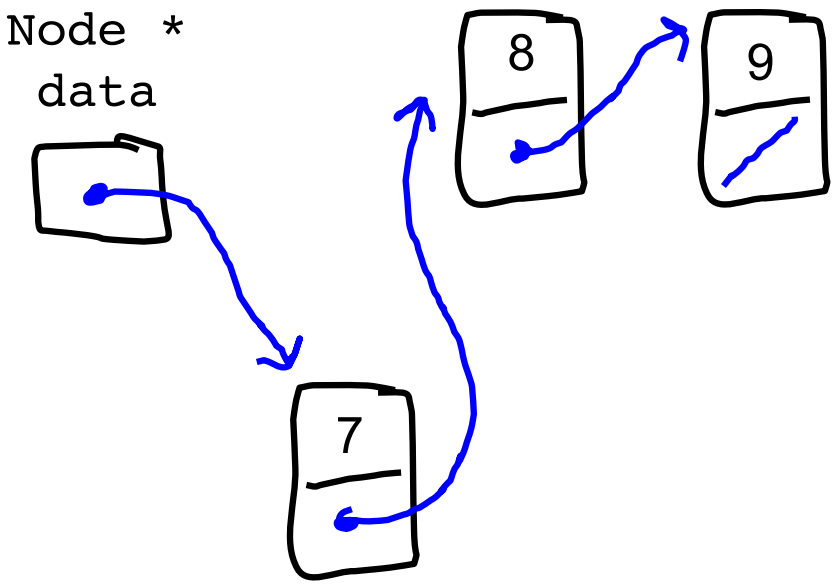
Stack: Big O of Push?

Stack: Big O of Pop?

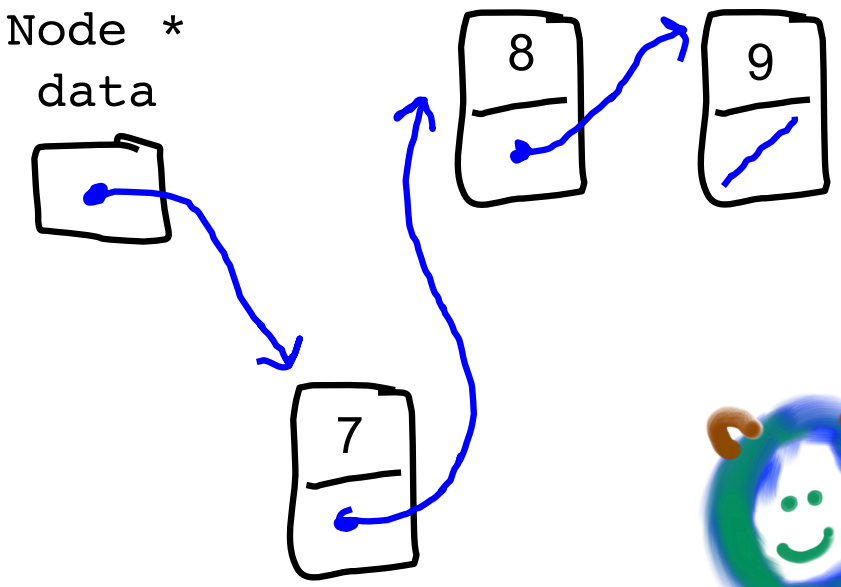
Queue?



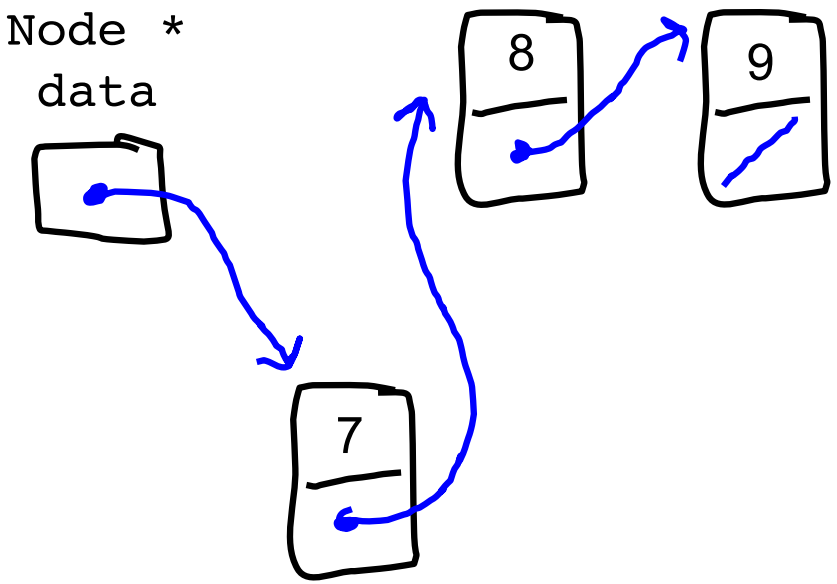
Queue Enqueue?



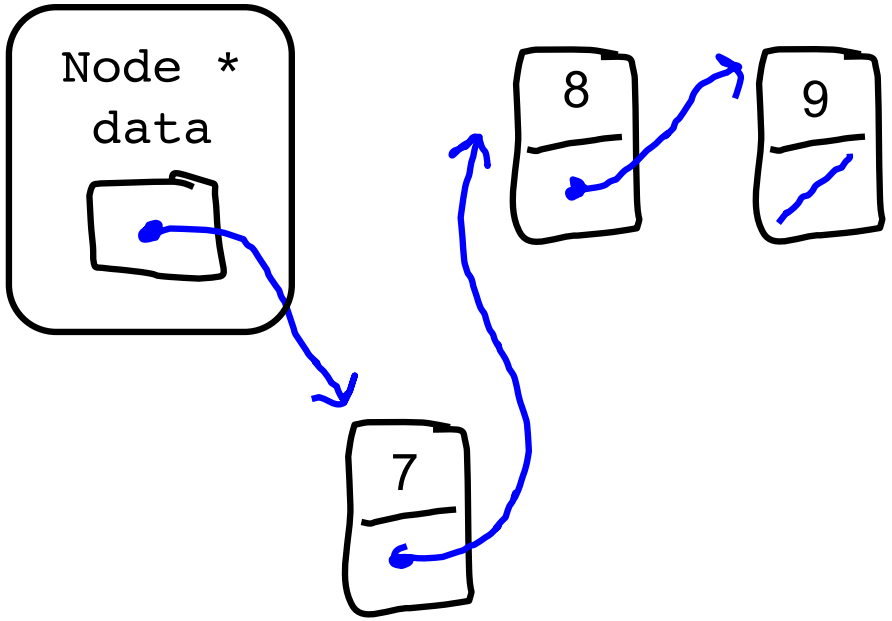
Queue Enqueue?



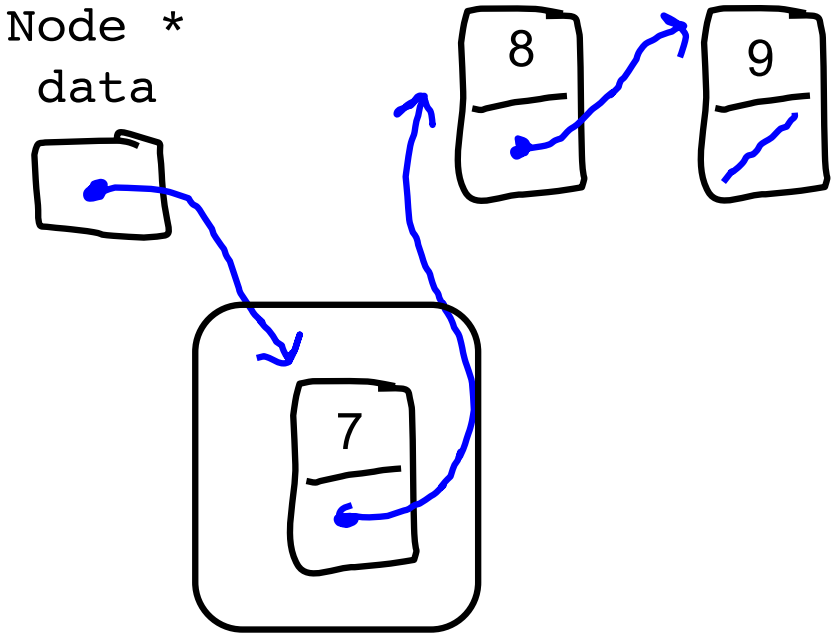
Queue Dequeue?



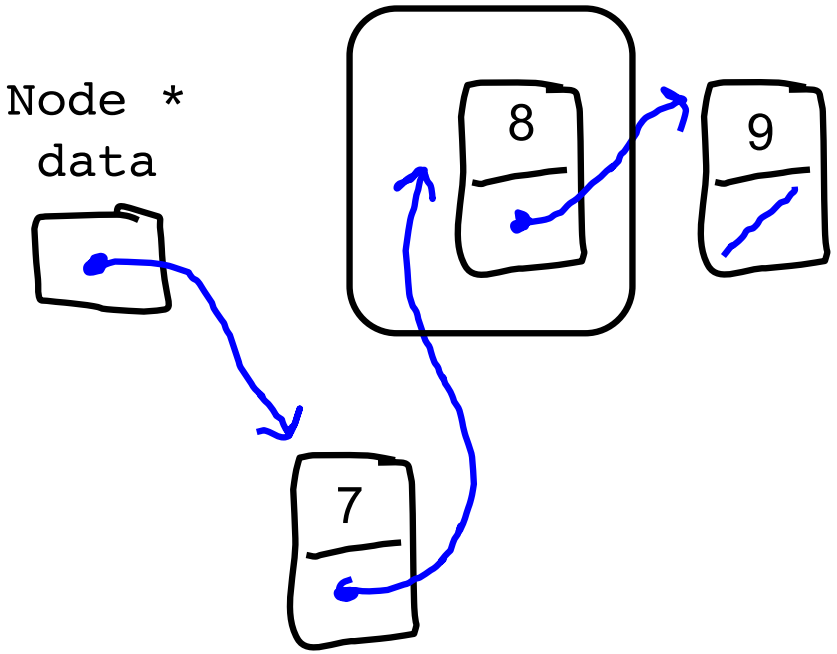
Queue Dequeue?



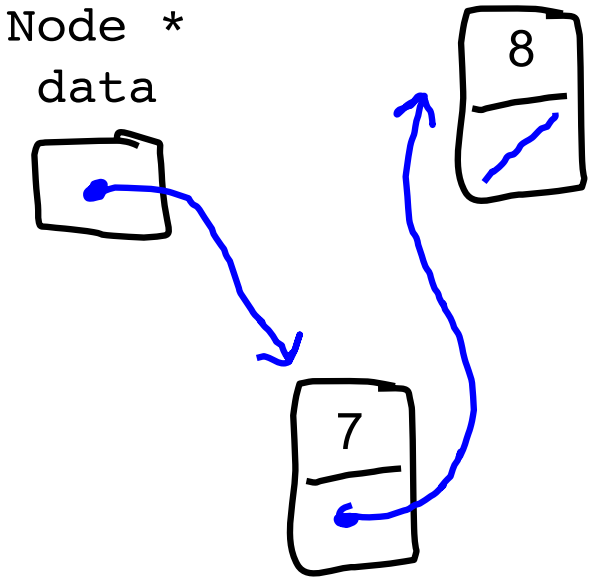
Queue Dequeue?



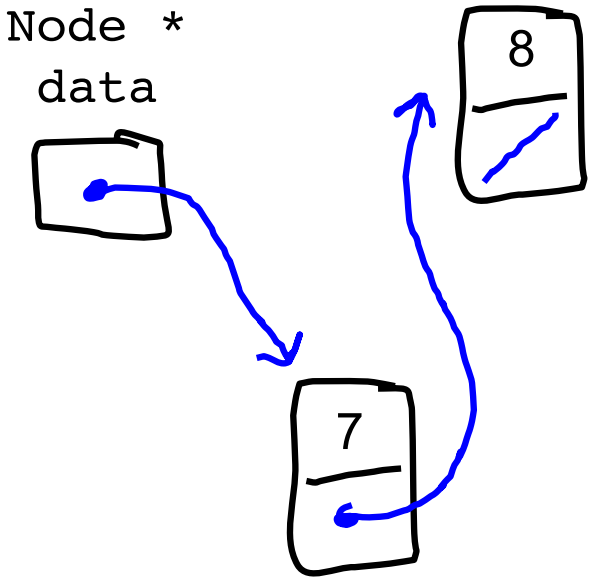
Queue Dequeue?



Queue Dequeue?



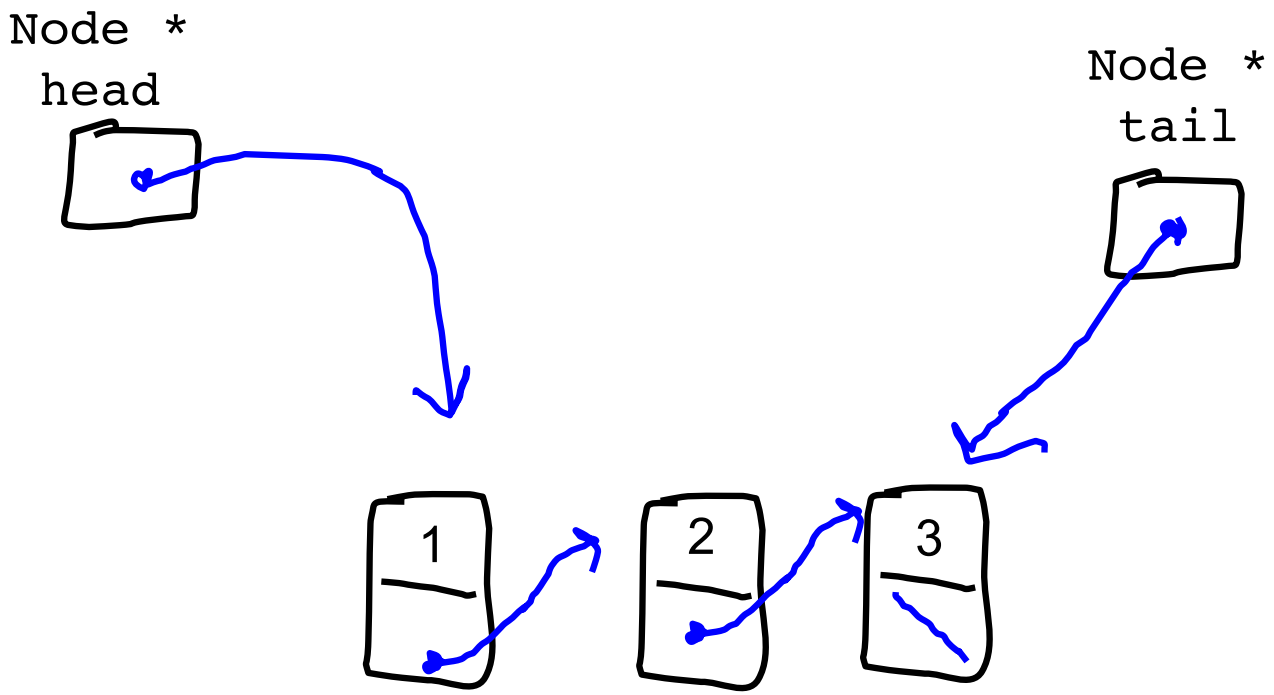
Queue Dequeue?



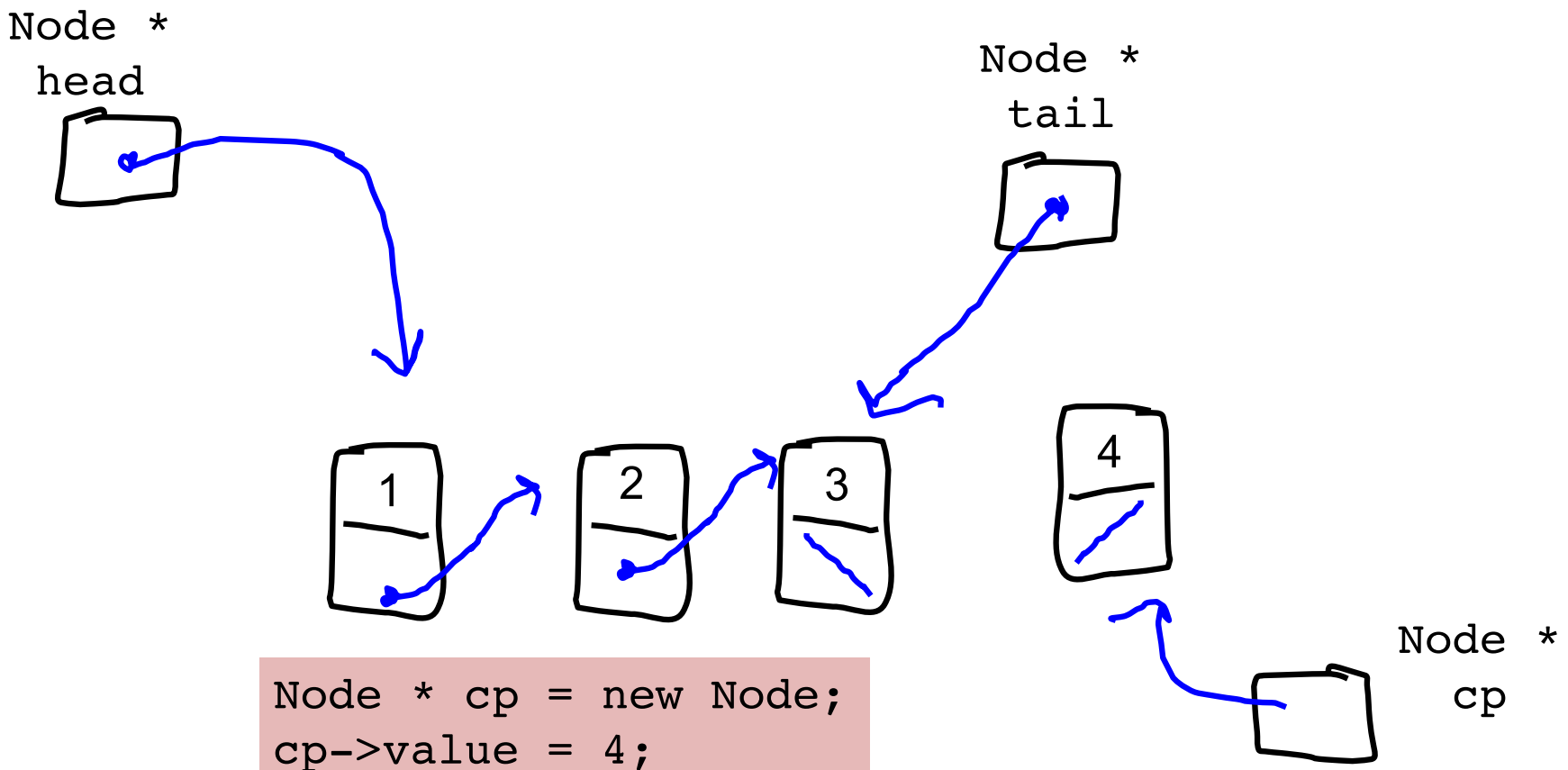
$$\mathcal{O}(n)$$

Always a Better Way

Actual Queue: Enqueue

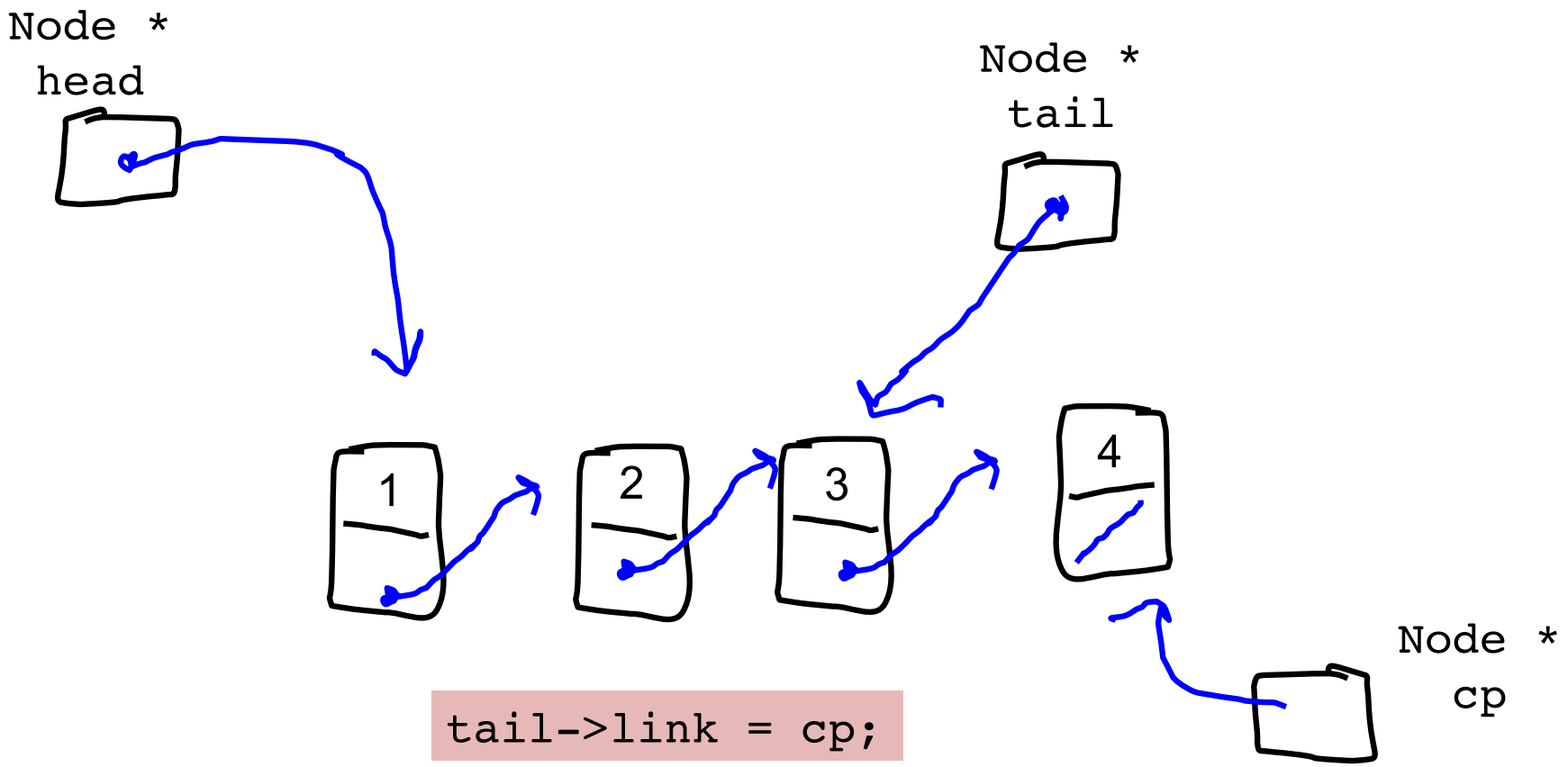


Actual Queue: Enqueue

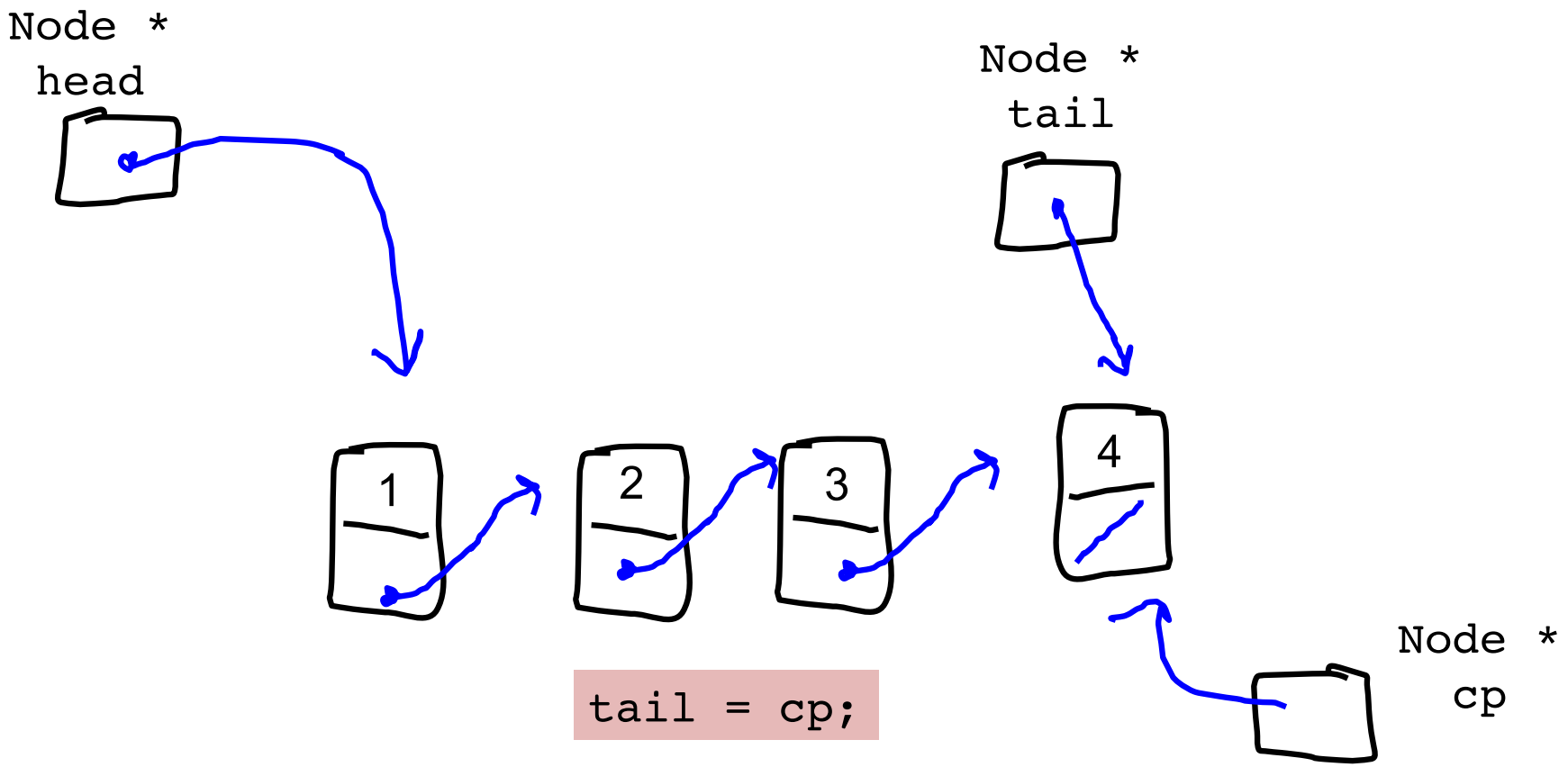



```
Node * cp = new Node;
cp->value = 4;
```

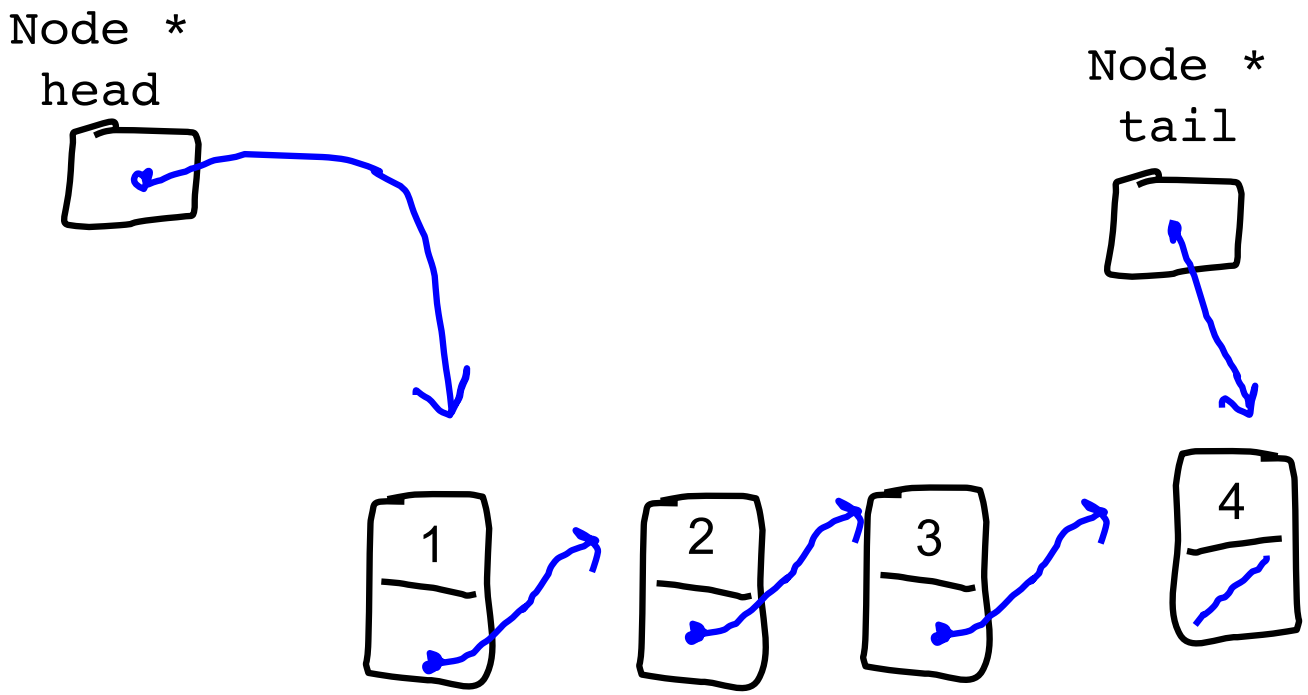
Actual Queue: Enqueue



Actual Queue: Enqueue

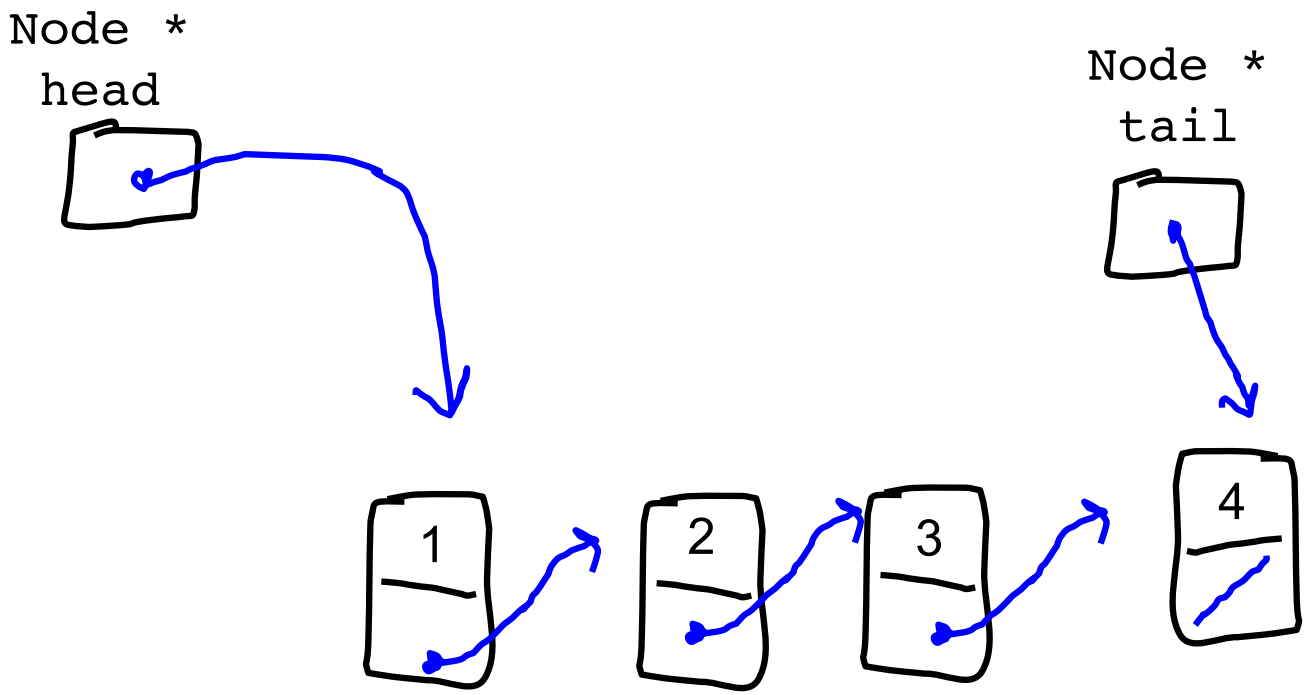


Actual Queue: Enqueue



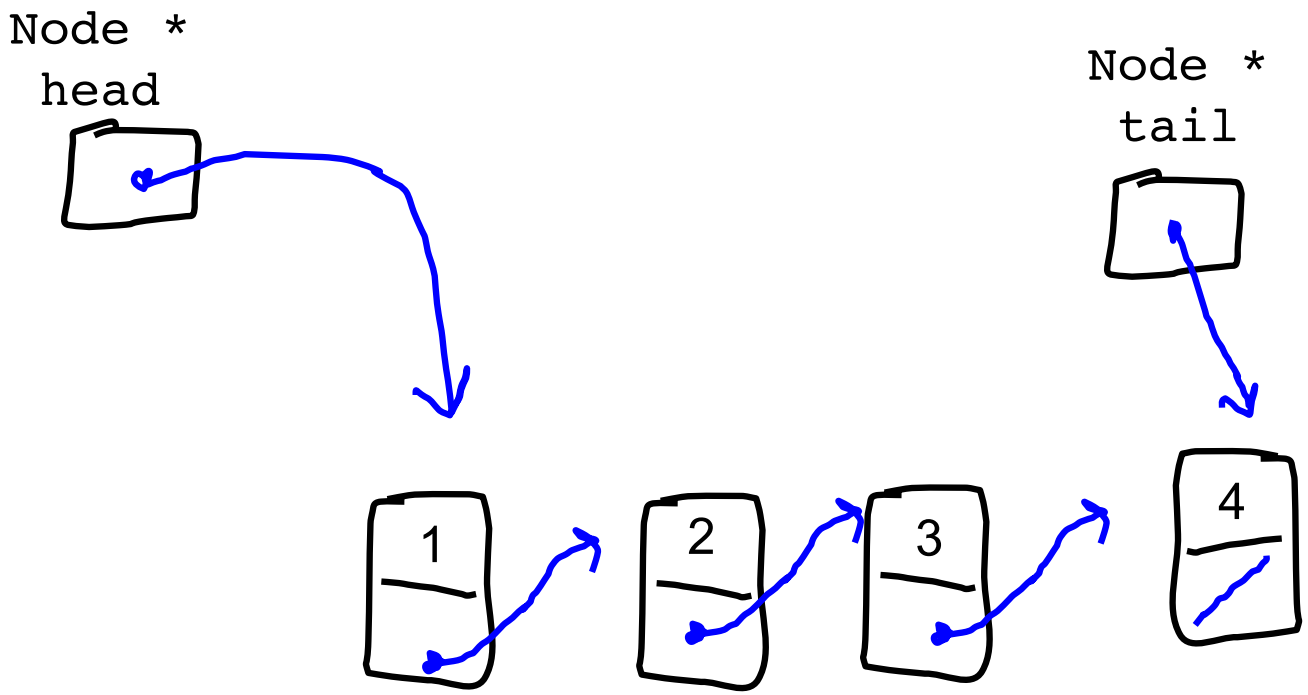

```
return;
```

Actual Queue: Enqueue

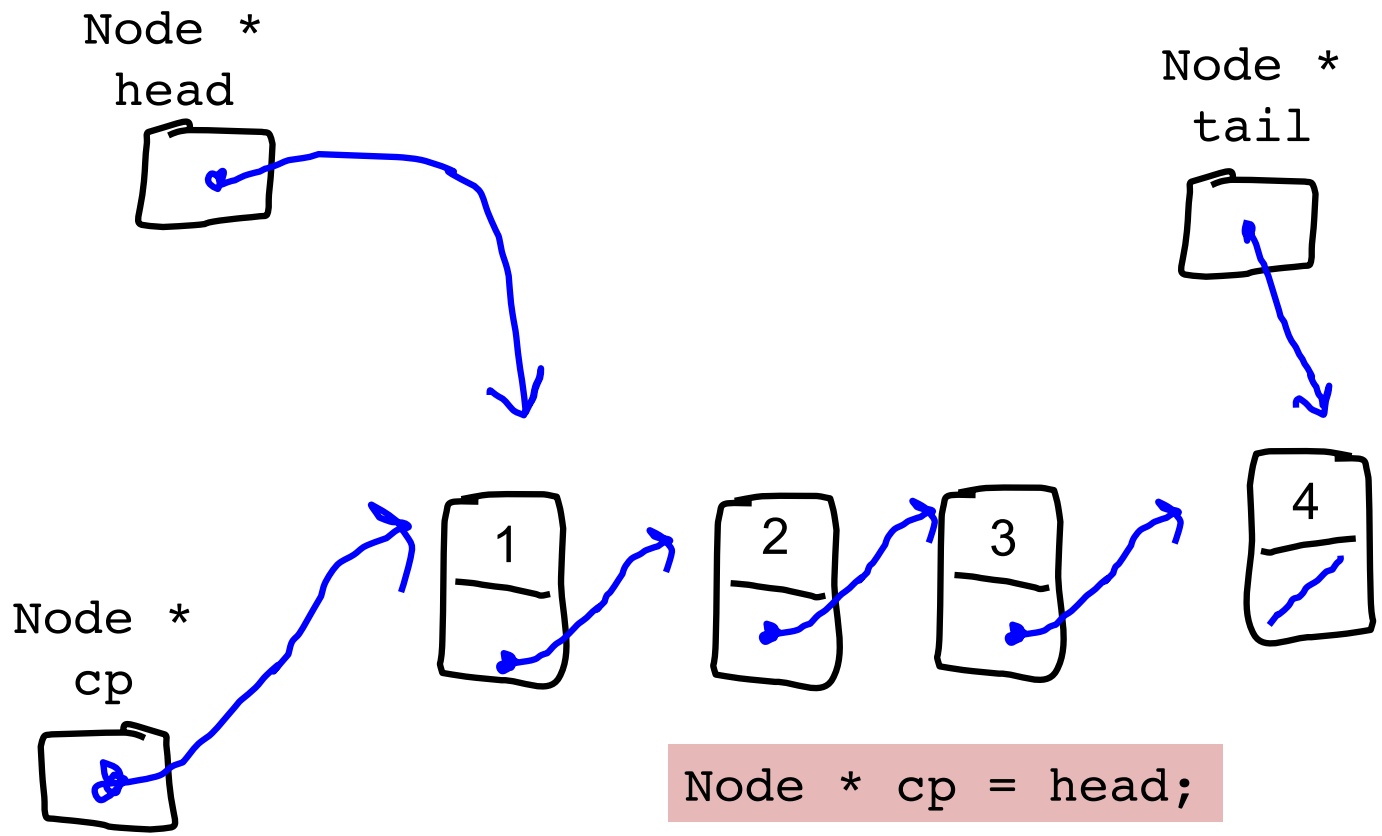


Dequeue

Actual Queue: Dequeue

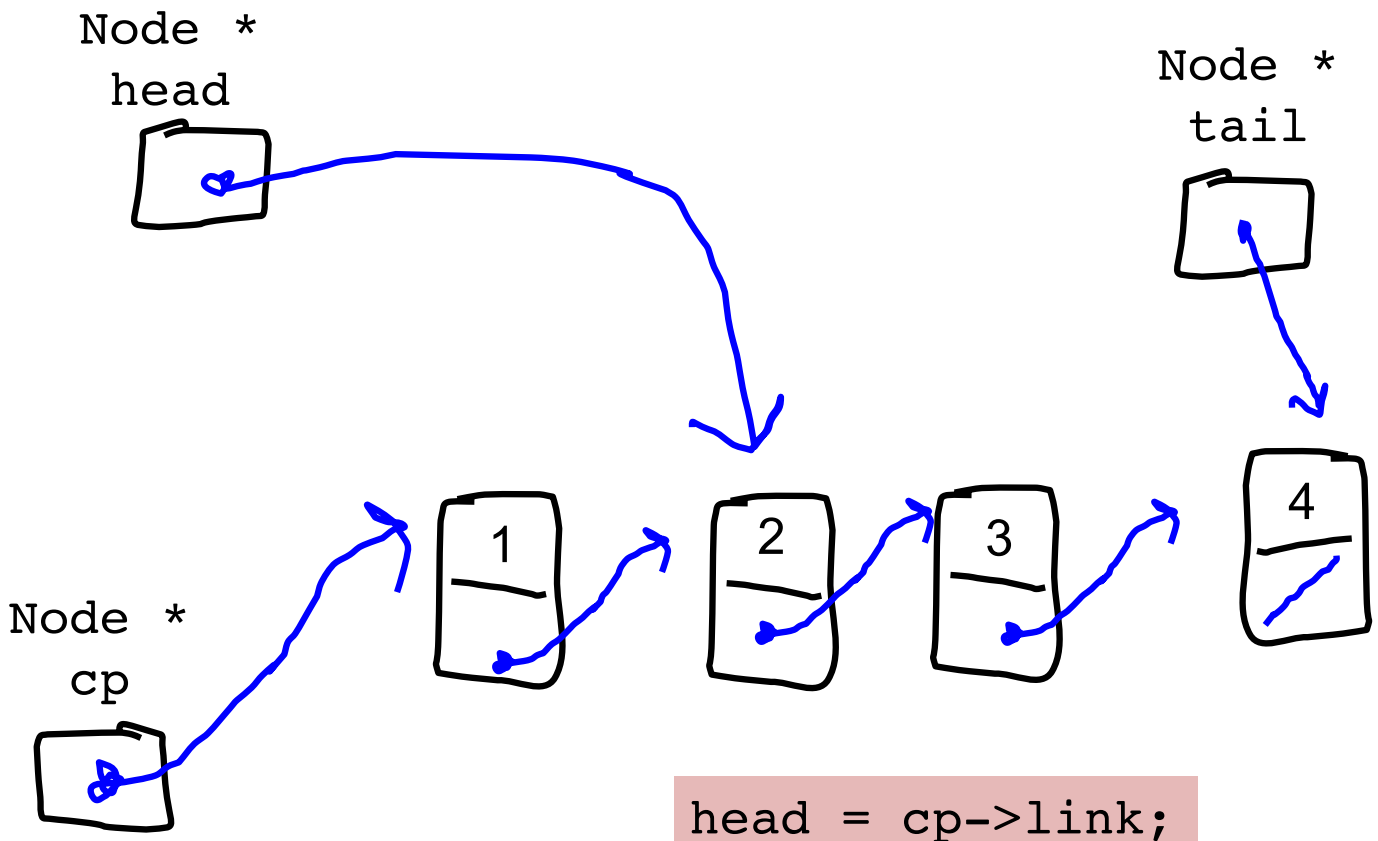


Actual Queue: Dequeue



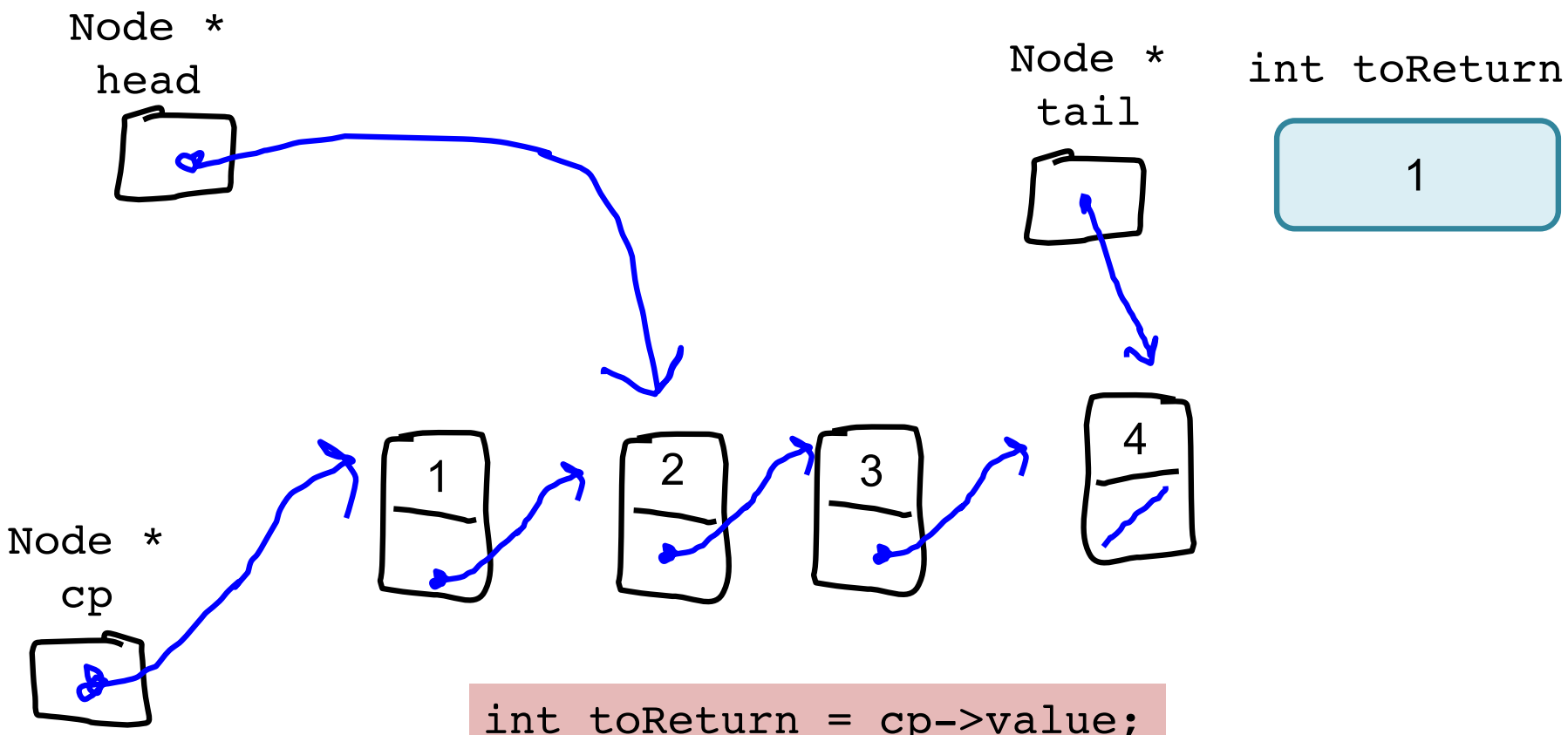

```
Node * cp = head;
```

Actual Queue: Dequeue

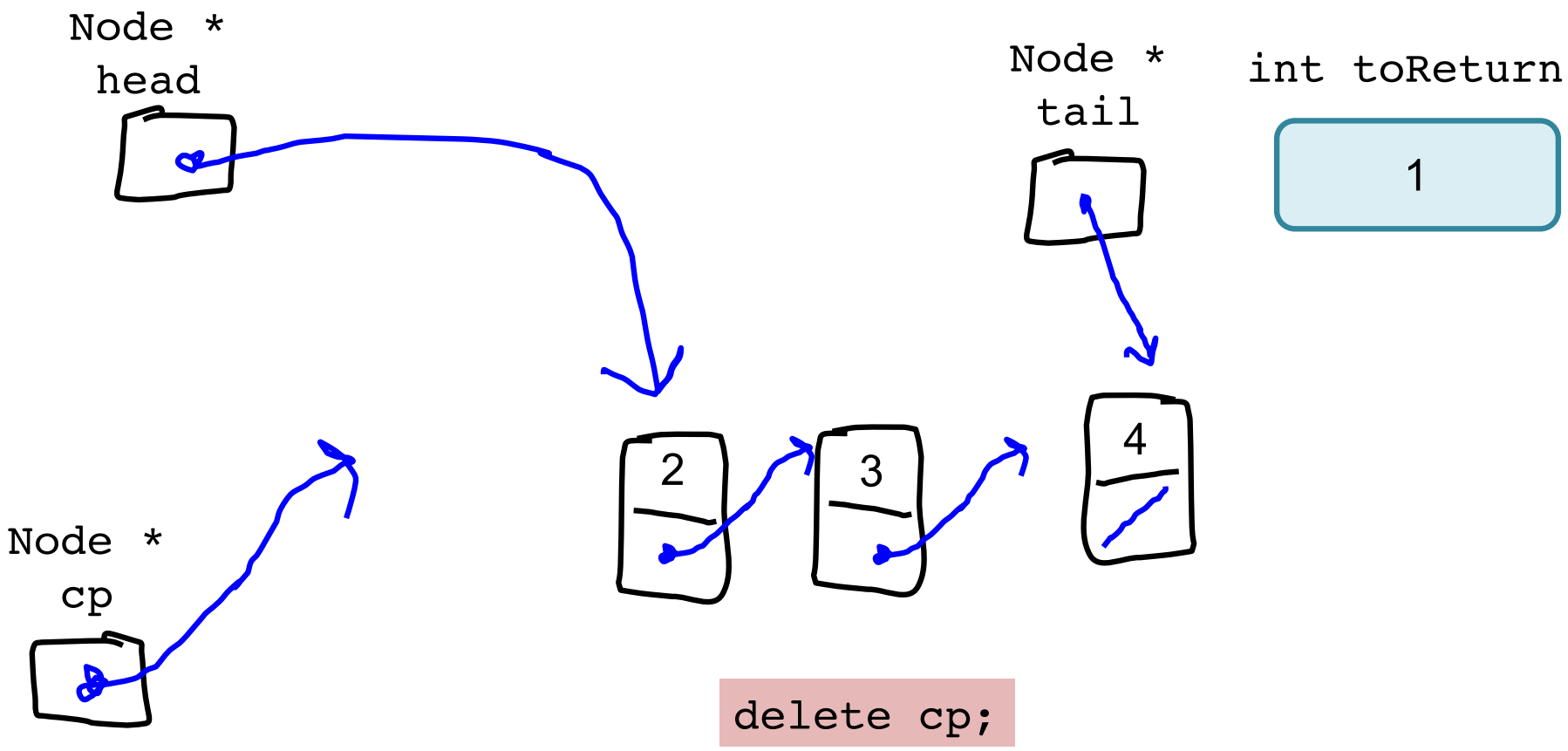



```
head = cp->link;
```

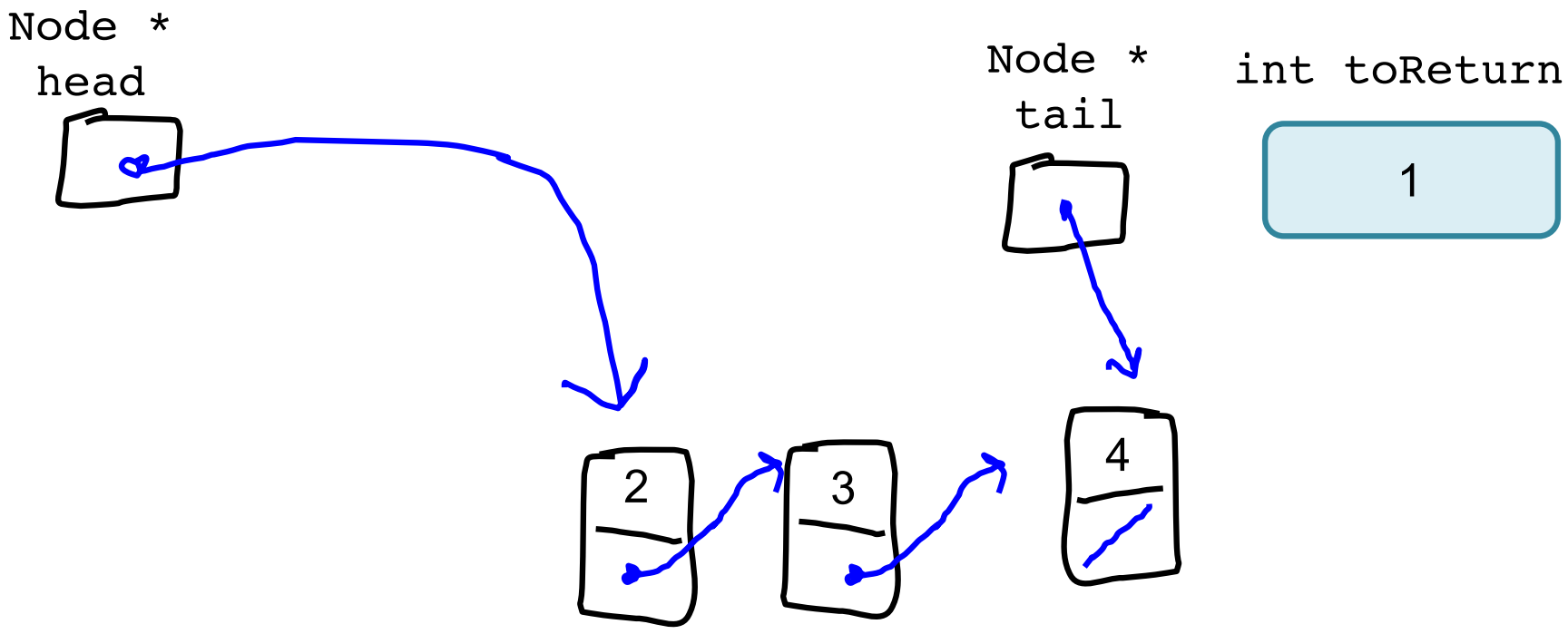
Actual Queue: Dequeue



Actual Queue: Dequeue

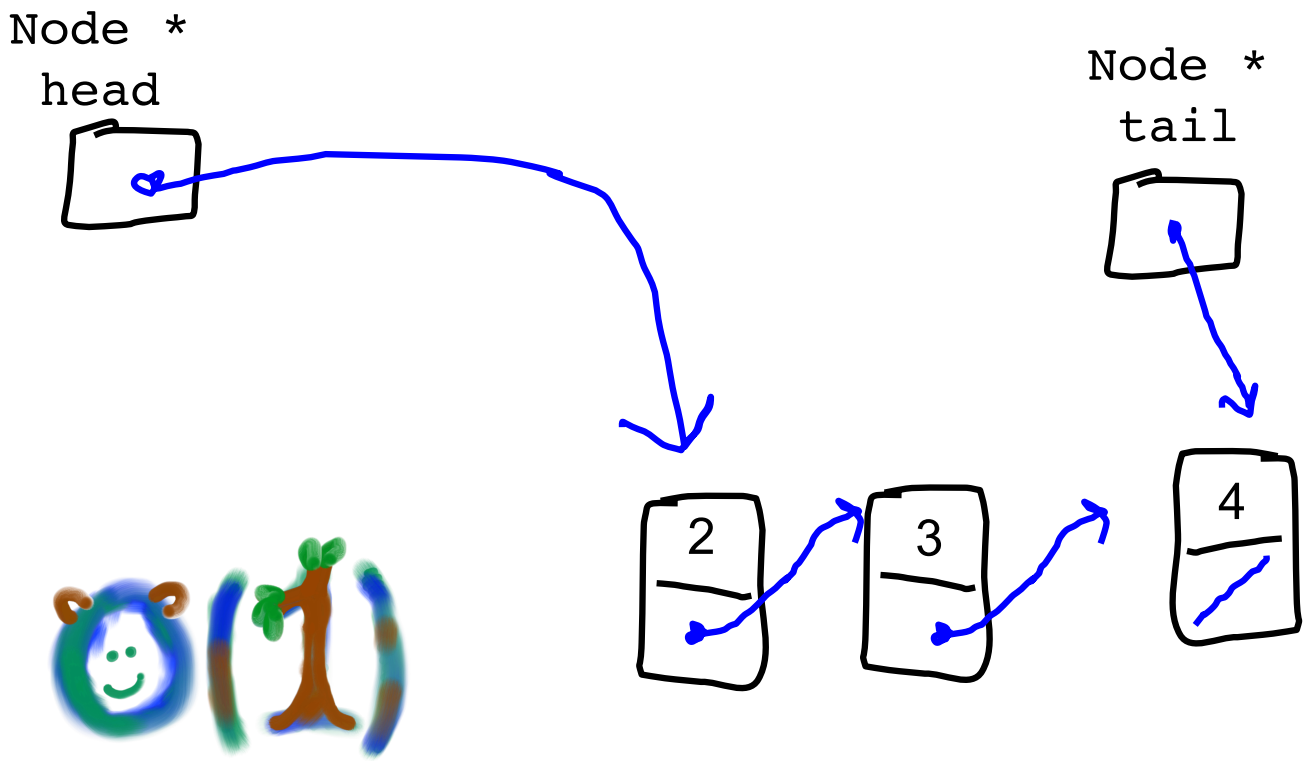


Actual Queue: Dequeue




```
return toReturn;
```

Actual Queue: Dequeue



Queue

```
class QueueInt {              // in QueueInt.h
public:
    QueueInt ();              // constructor

    void enqueue(int value); // append a value
    int dequeue();             // return the first-in value

private:
    struct Node {
      int value;
      Node * link;
    };
    Node * head;      // has a pointer to the first node
    Node * tail;      // and a pointer to the last node
};
```

Queue Implementation

```
void QueueInt::enqueue(int v) {
    Node * temp = new Node;
    temp->value = v;
    tail->link = temp;
    tail = temp;
}

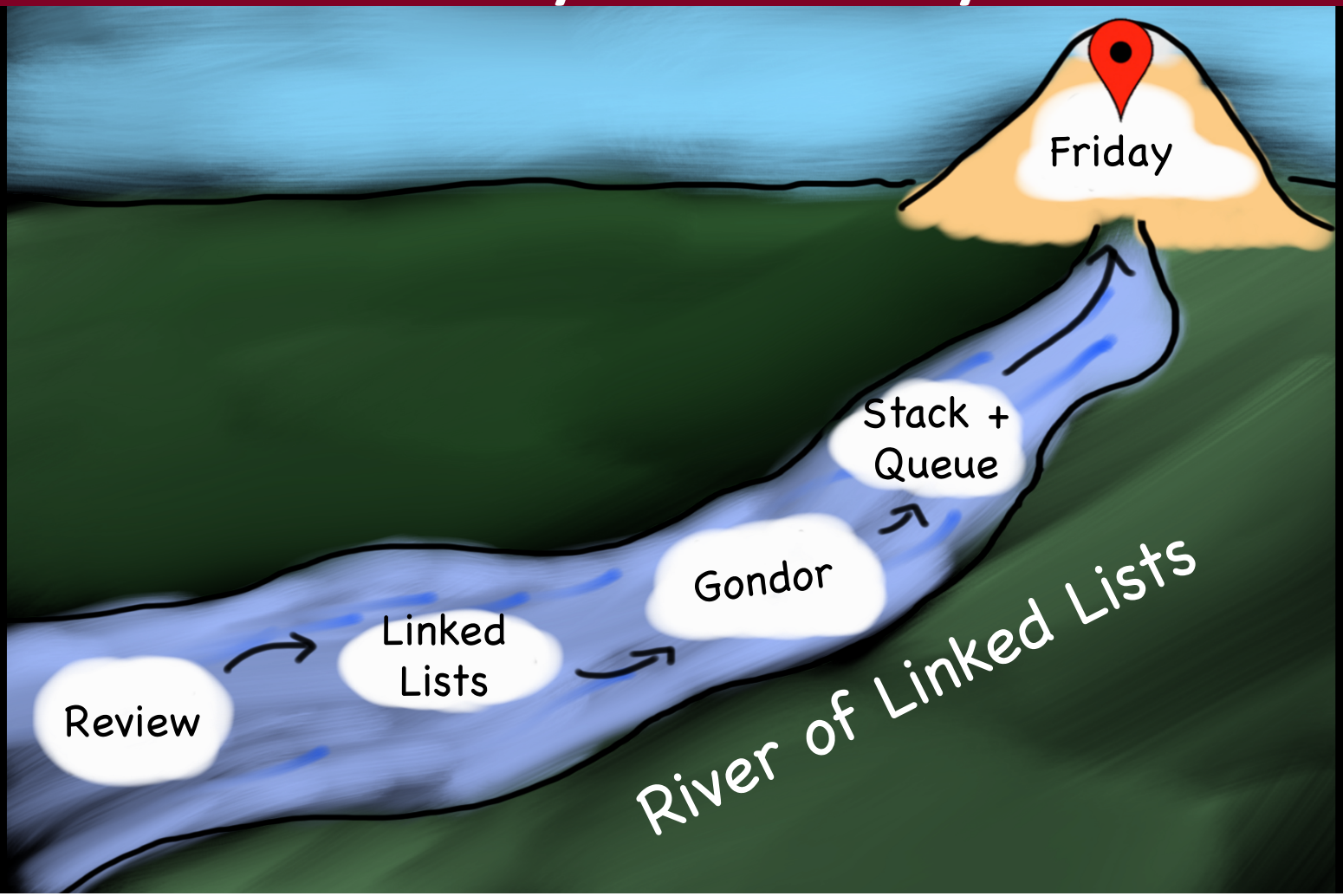
int QueueInt::dequeue() {
    int toReturn = head->value;
    Node * temp = head;
    head = temp->link;
    delete temp;
    return toReturn;
}
```

Linked Lists are Excellent

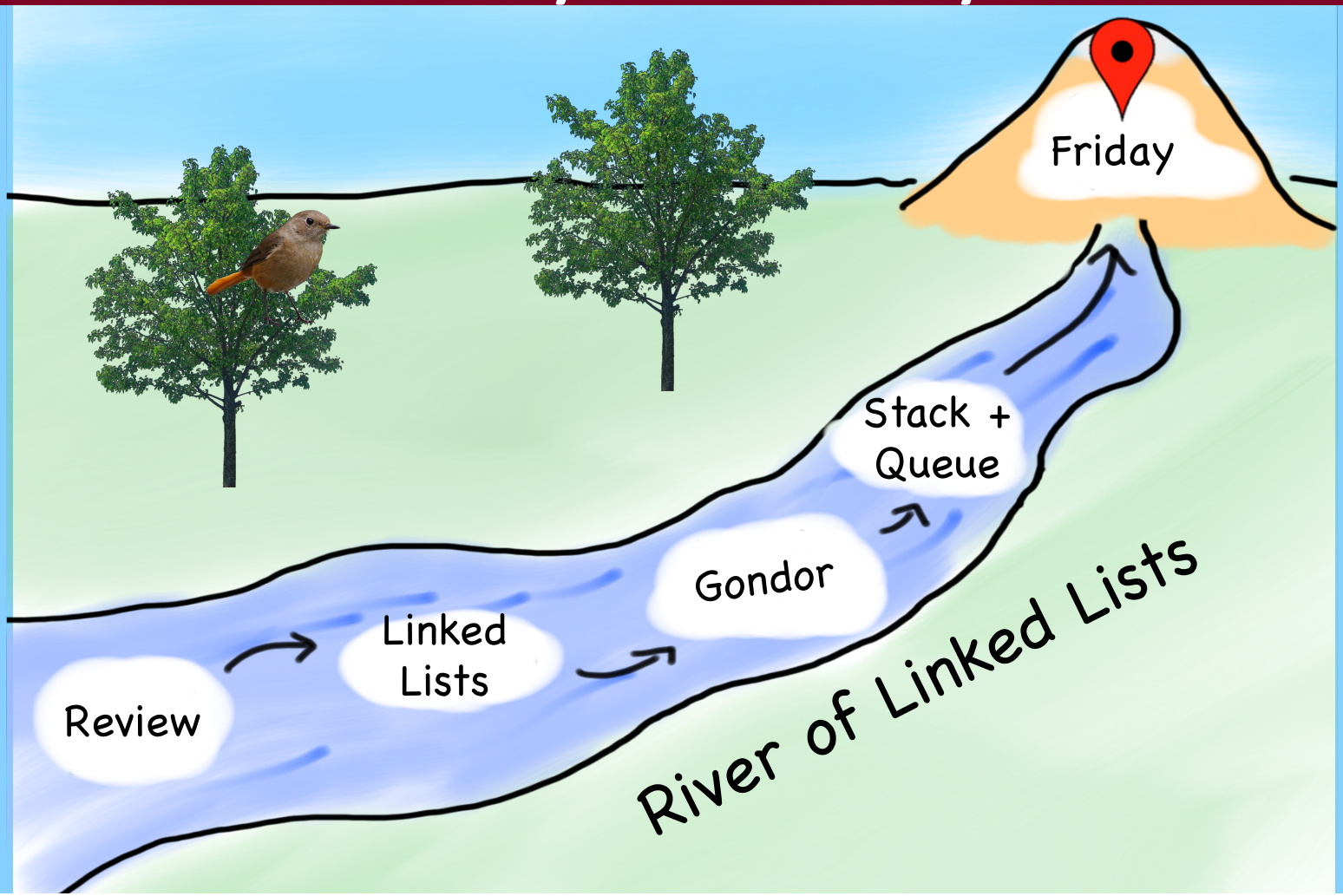
	Worst
Stack Push	$\mathcal{O}(1)$
Stack Pop	$\mathcal{O}(1)$
Queue Enqueue	$\mathcal{O}(1)$
Queue Dequeue	$\mathcal{O}(1)$

Today's Journey

Today's Journey



Today's Journey



Today's Goals

1. Learn linked lists
2. See how Stack + Queue work
3. Get ready for trees…