

CS 106B

Lecture 16: Linked Lists

Monday, April 8, 2017

Programming Abstractions
Spring 2017
Stanford University
Computer Science Department

Lecturer: Chris Gregg

reading:
Programming Abstractions in C++, Chapter 11

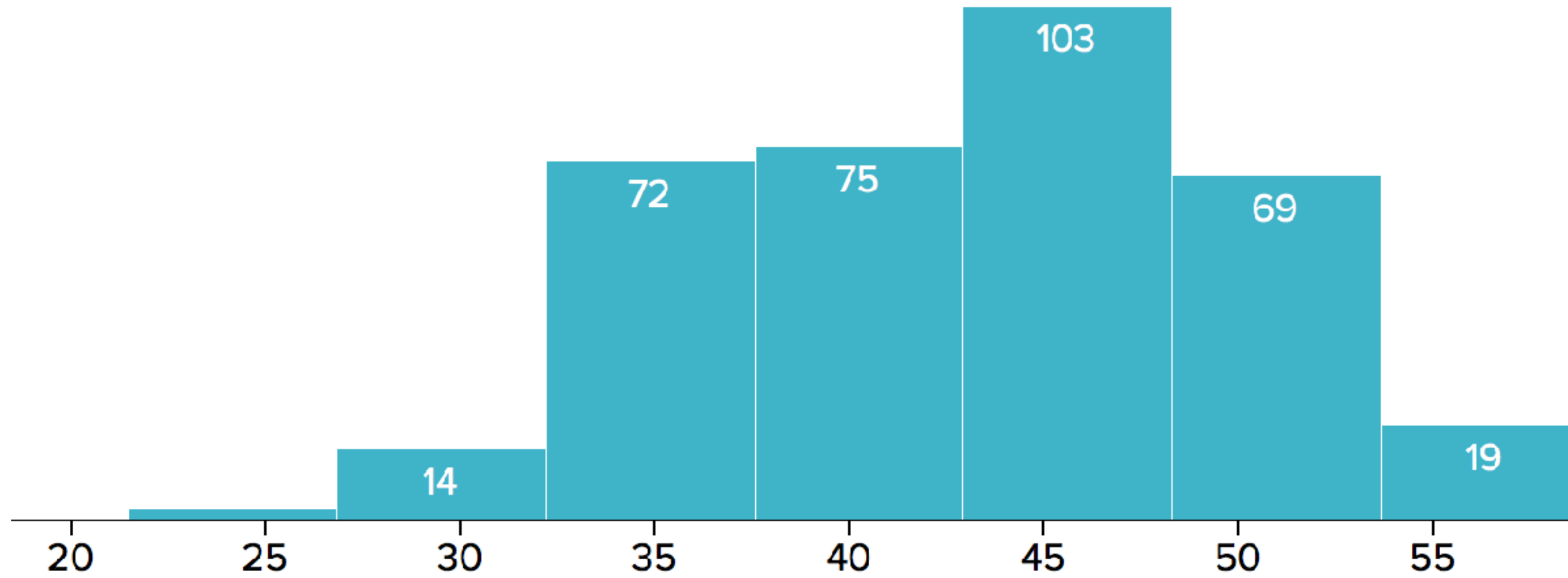


Today's Topics

- Logistics
 - Tiny feedback:
 - favorite type of dog? Tough choice...probably Corgis. Or Labs.
 - favorite programming language? Tough choice...depends on the situation!
 - C++: fast, robust, powerful
 - C: less to worry about than C++
 - Python: so fast to code in, but can be slow
 - Javascript: need something on the web?
 - Haskell: so different from regular programming
 - Piet: ???
- Linked Lists
 - Could you architect a Queue?
 - Nodes
 - Linked Lists
 - The Towers of Gondor
 - Do nodes have names?
 - Big O?
 - Stack and Queue made from a Linked List



Midterm



MEDIAN

43.0

MAXIMUM

59.0

MEAN

42.8

STD DEV

7.28

MEDIAN

72.88%

MAXIMUM

100.0%

MEAN

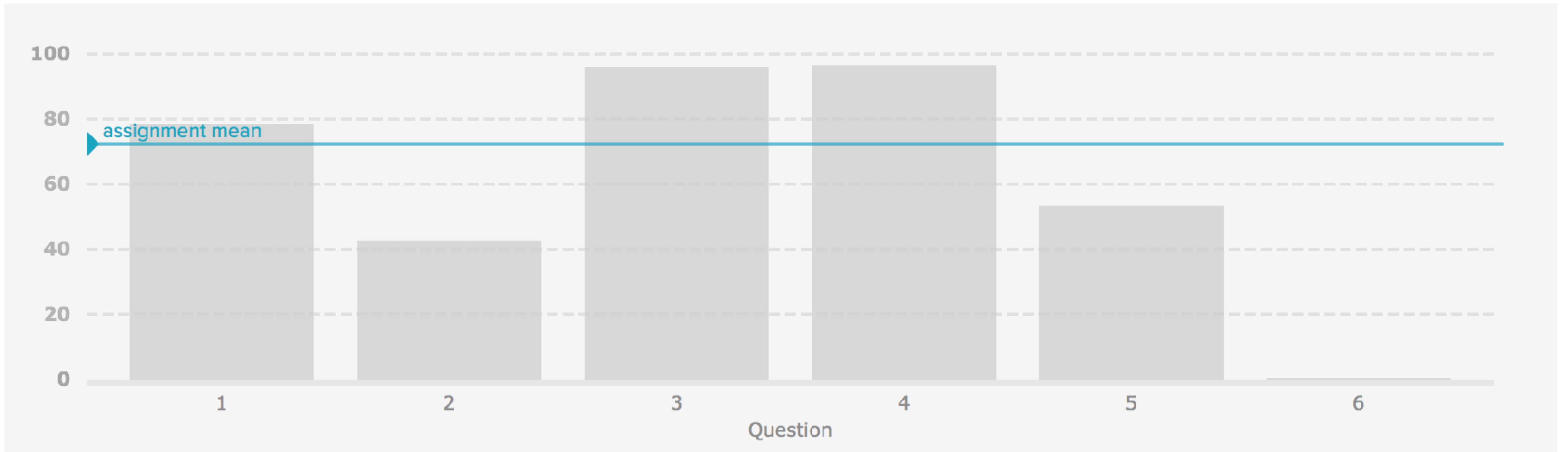
72.55%

STD DEV

12.33%



Midterm



Your job: Architect a 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

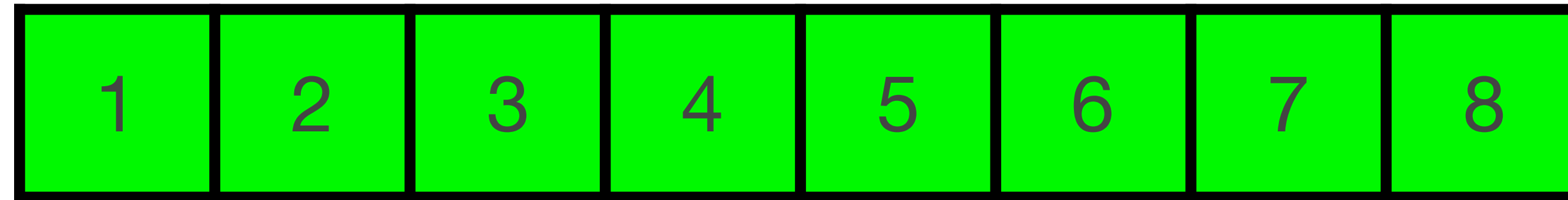
private:
    Vector<int> data; // member variables
};
```



You're next!

back

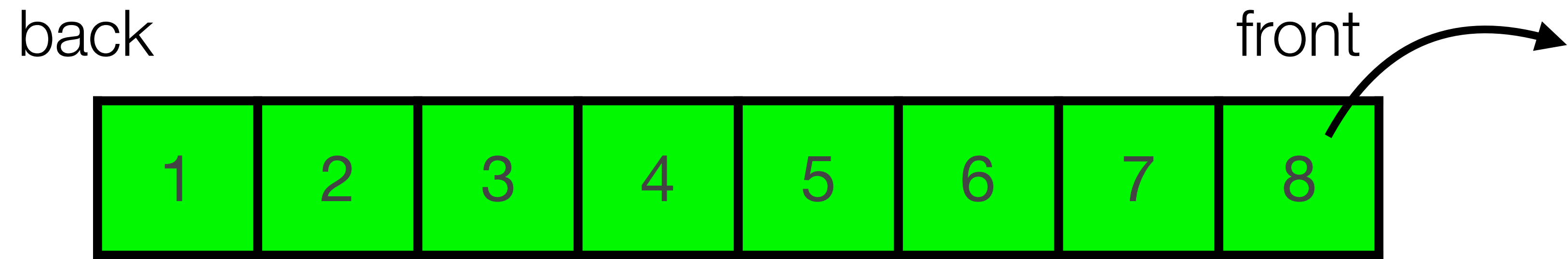
front



dequeue()



You're next!



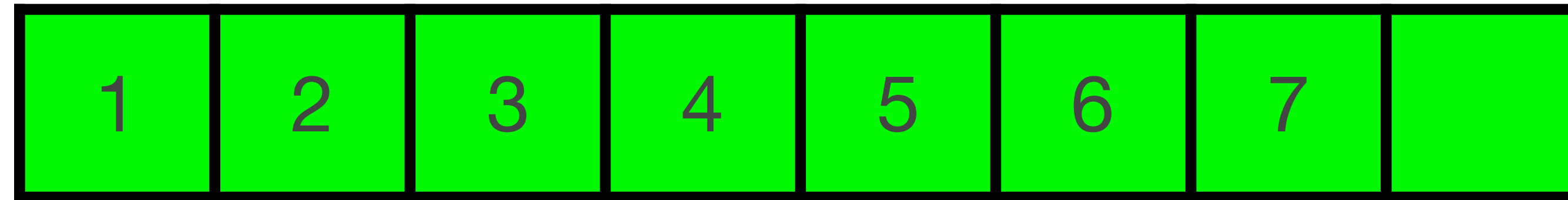
dequeue()



Excuse Me, Coming Through

back

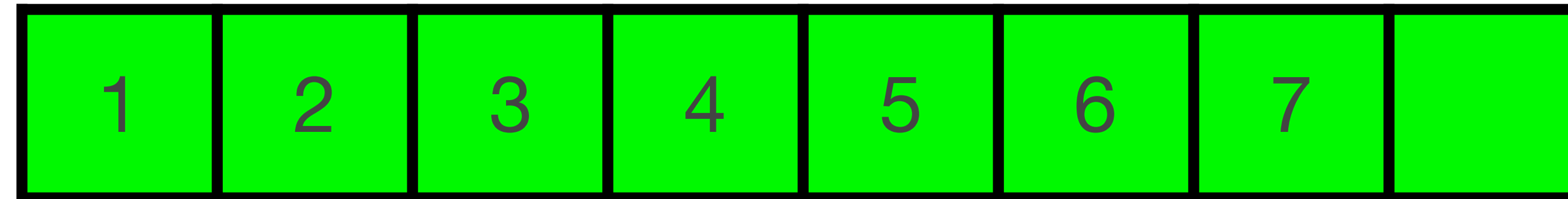
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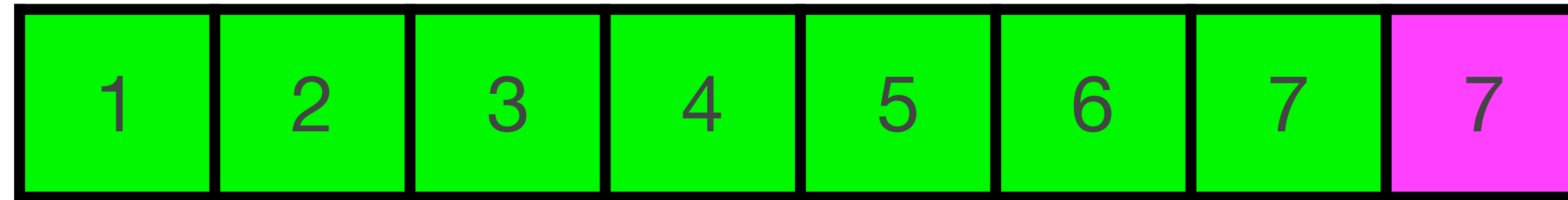
enqueue(42)



Excuse Me, Coming Through

back

front



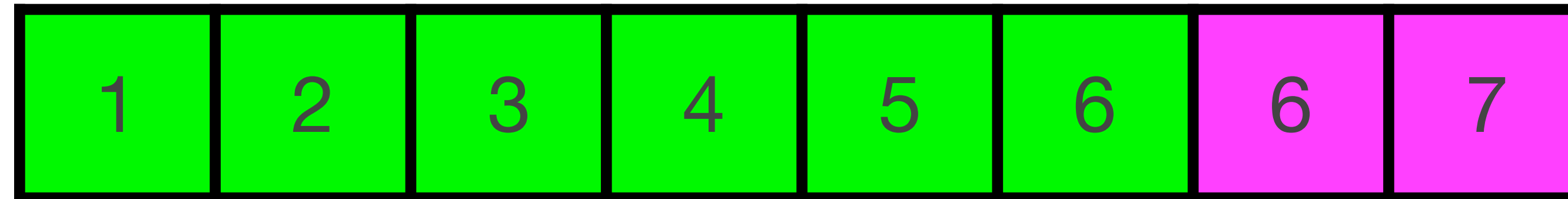
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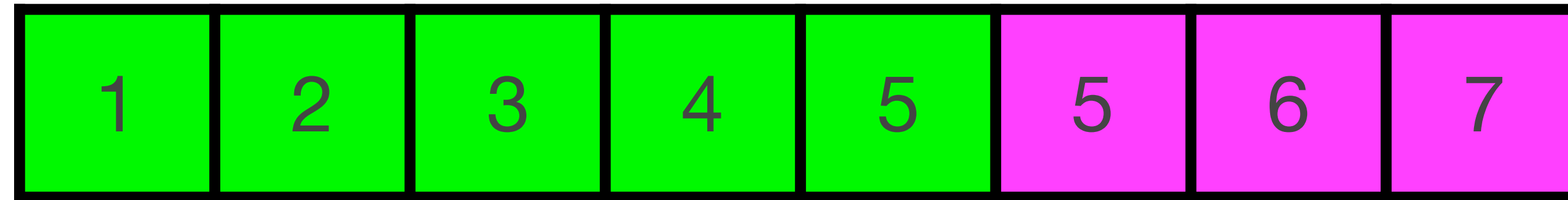
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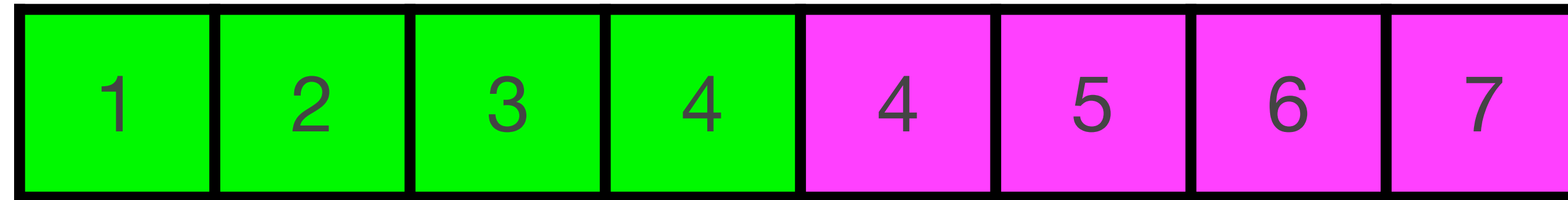
enqueue(42)



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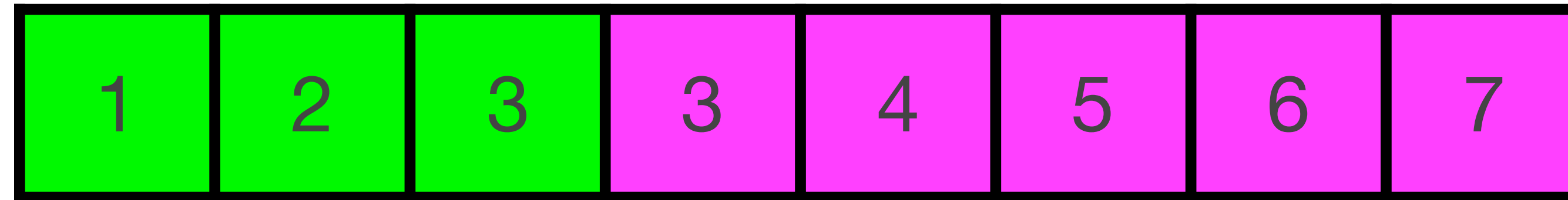
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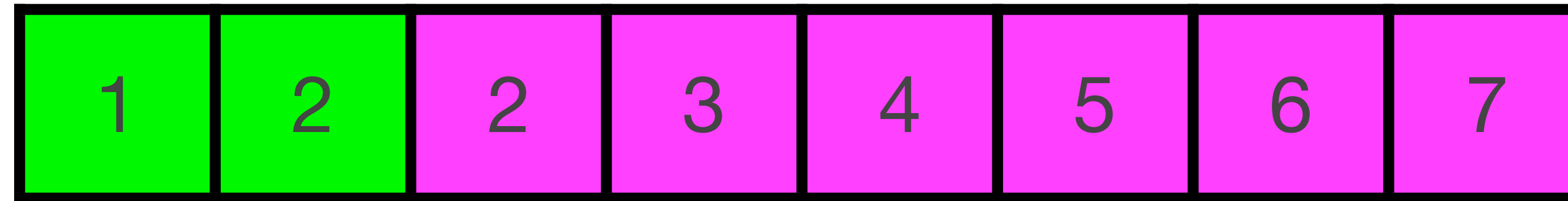
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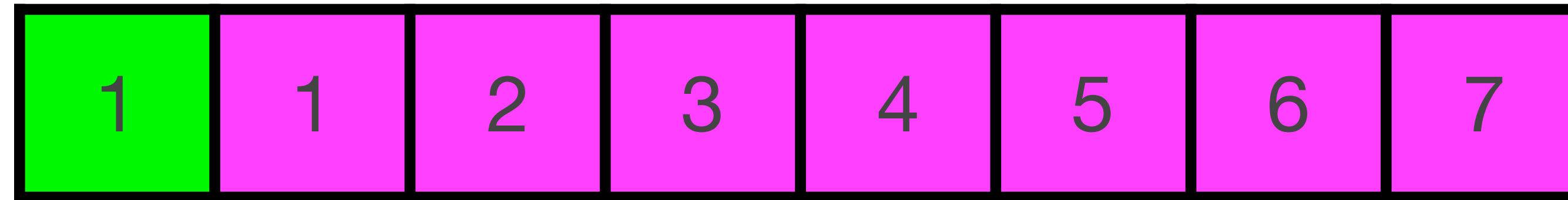
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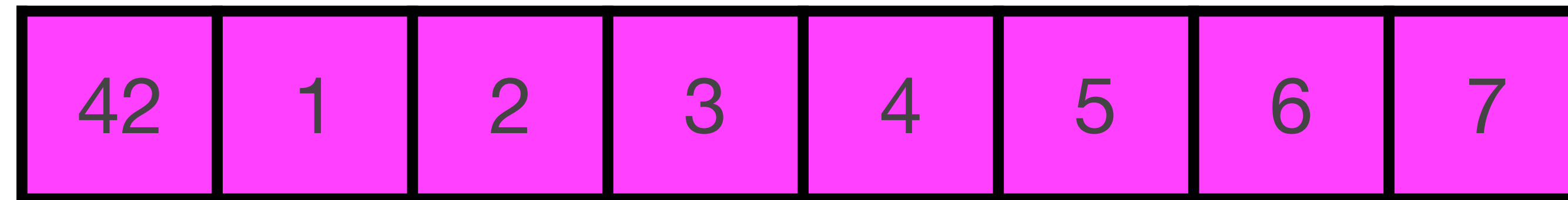
enqueue(42)



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enqueue(42)



Queue as Vector: Big O

Enqueue: $O(n)$

Dequeue: $O(1)$

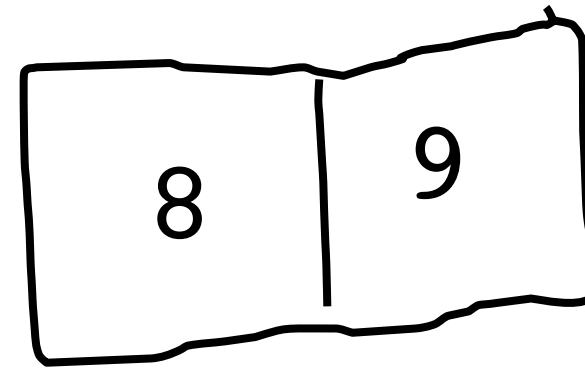
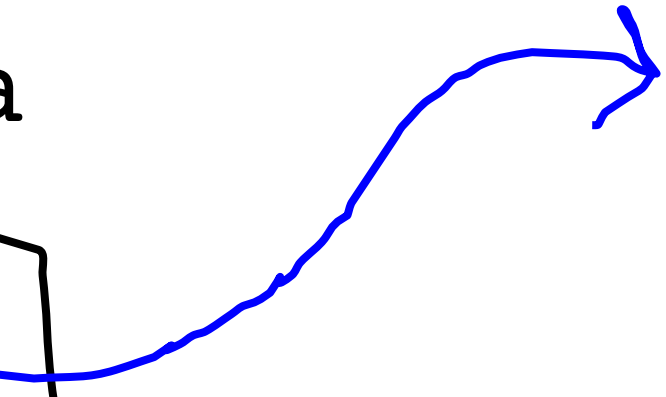
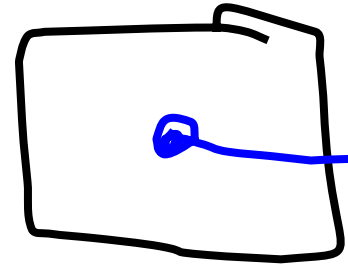


**WE CAN DO
BETTER**



And Now for Something Completely Different

```
int *  
data
```

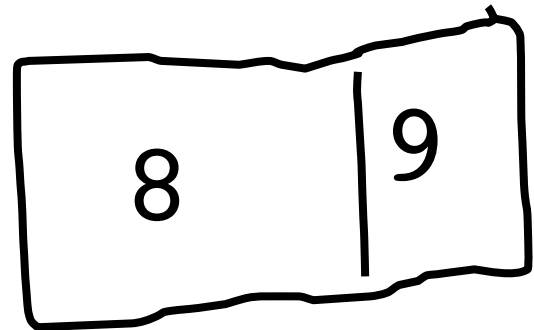
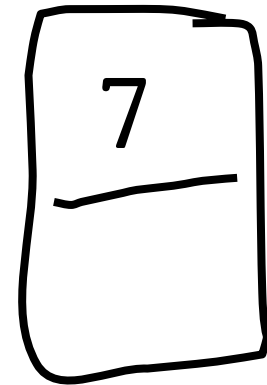
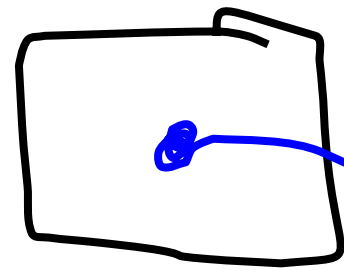


```
enqueue(7)
```



And Now for Something Completely Different

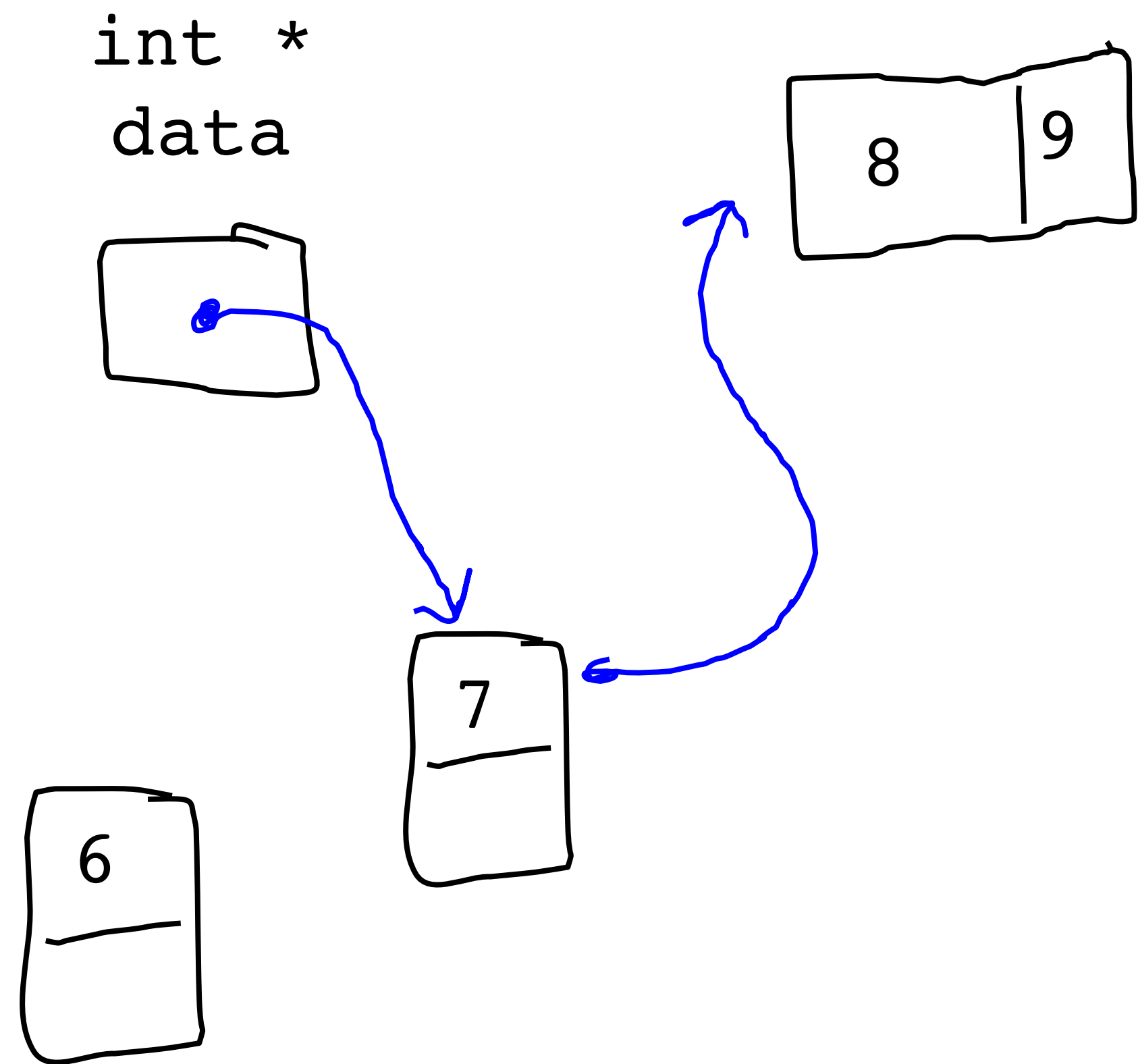
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int *  
data
```



```
enqueue(7)
```



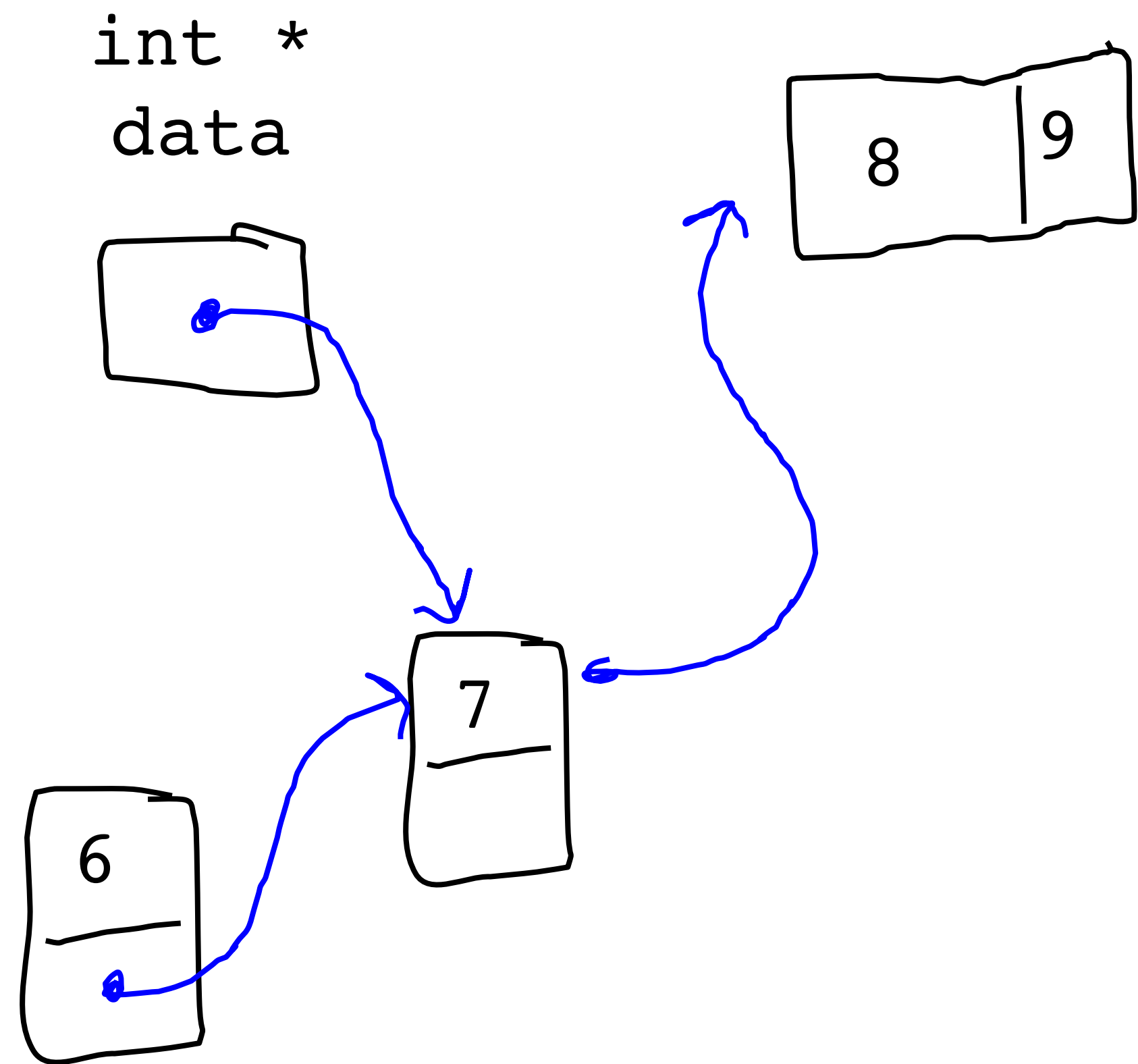
And Now for Something Completely Different



enqueue(6)



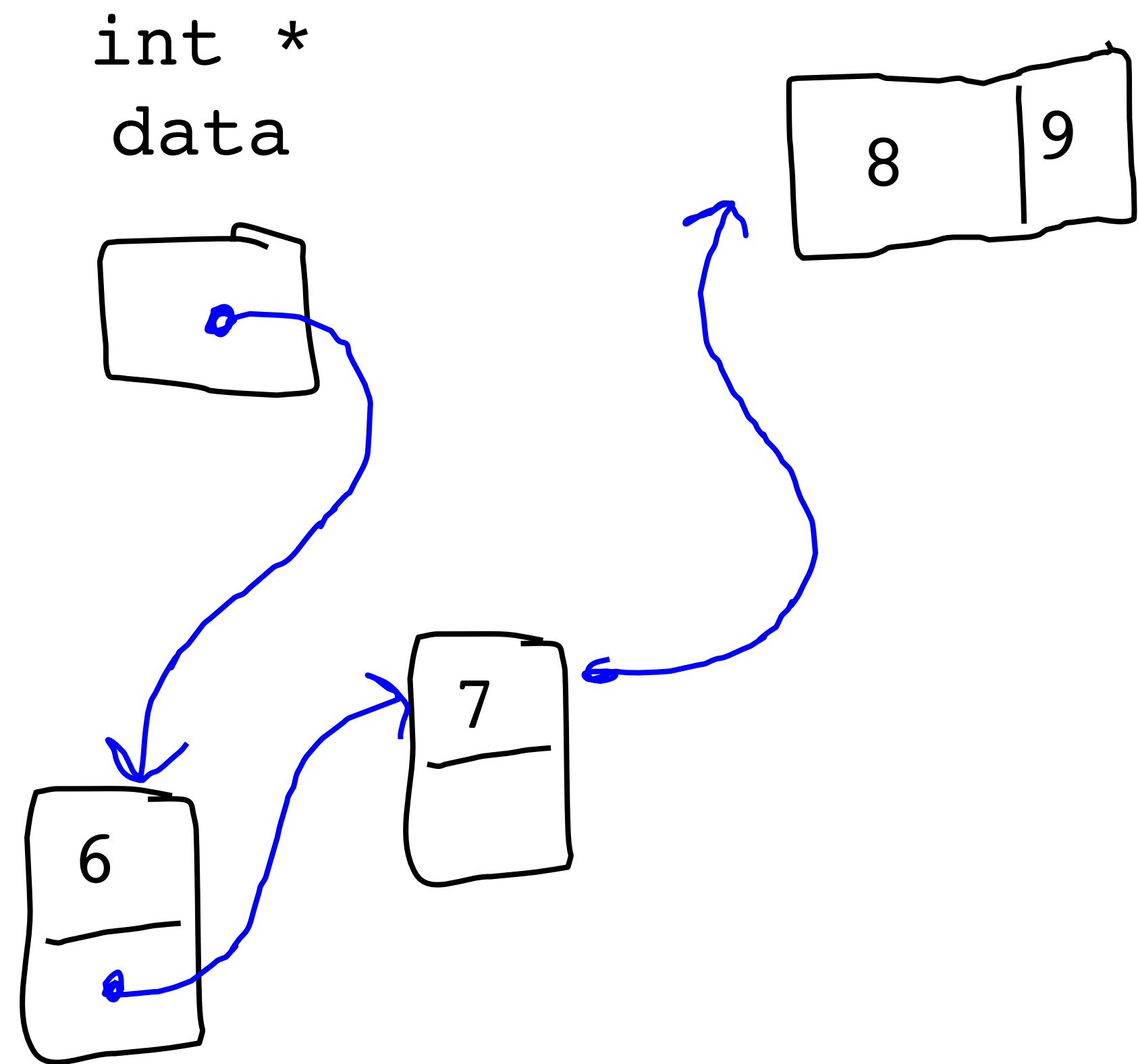
And Now for Something Completely Different



enqueue(6)



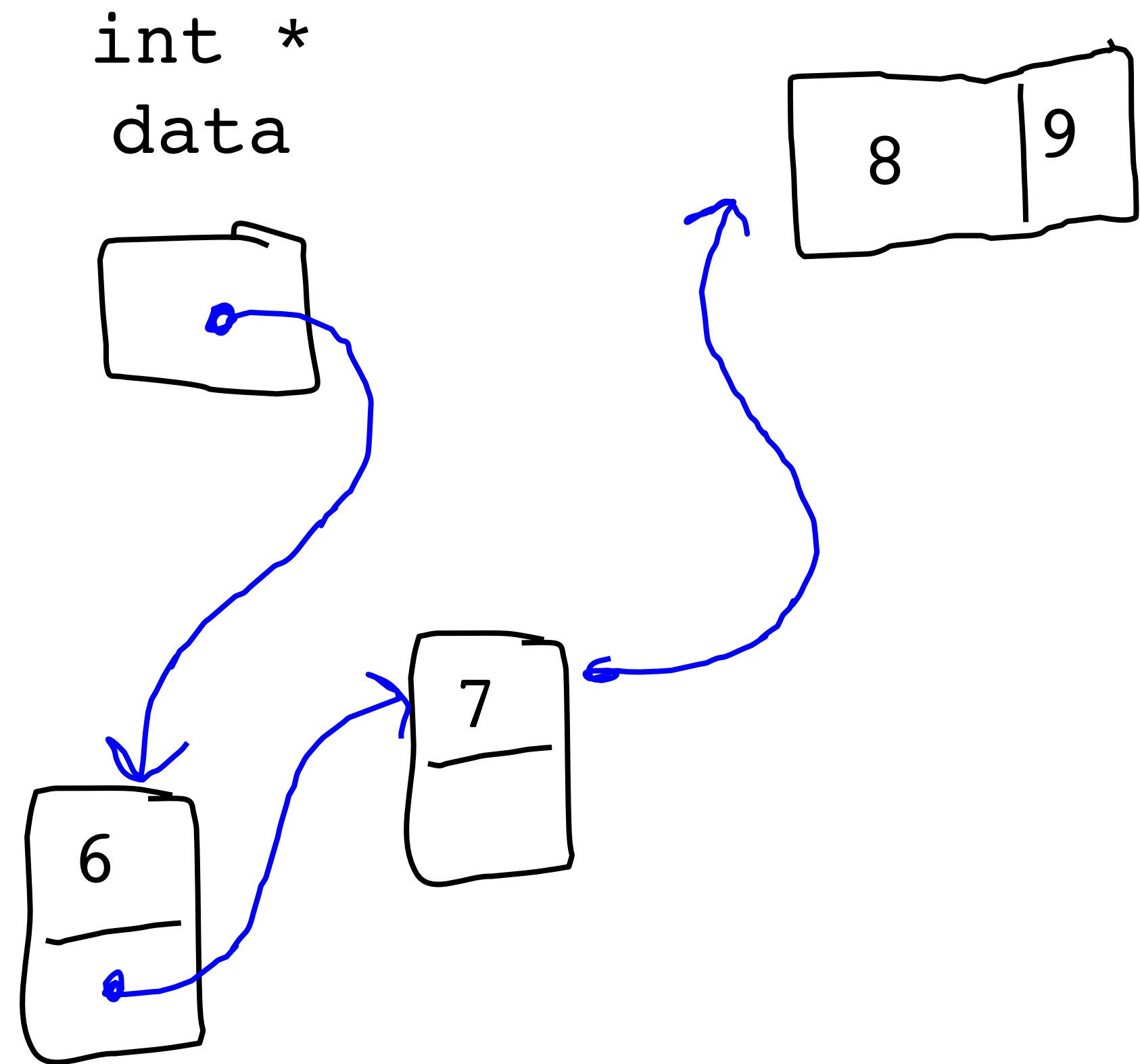
And Now for Something Completely Different



enqueue(6)



And Now for Something Completely Different

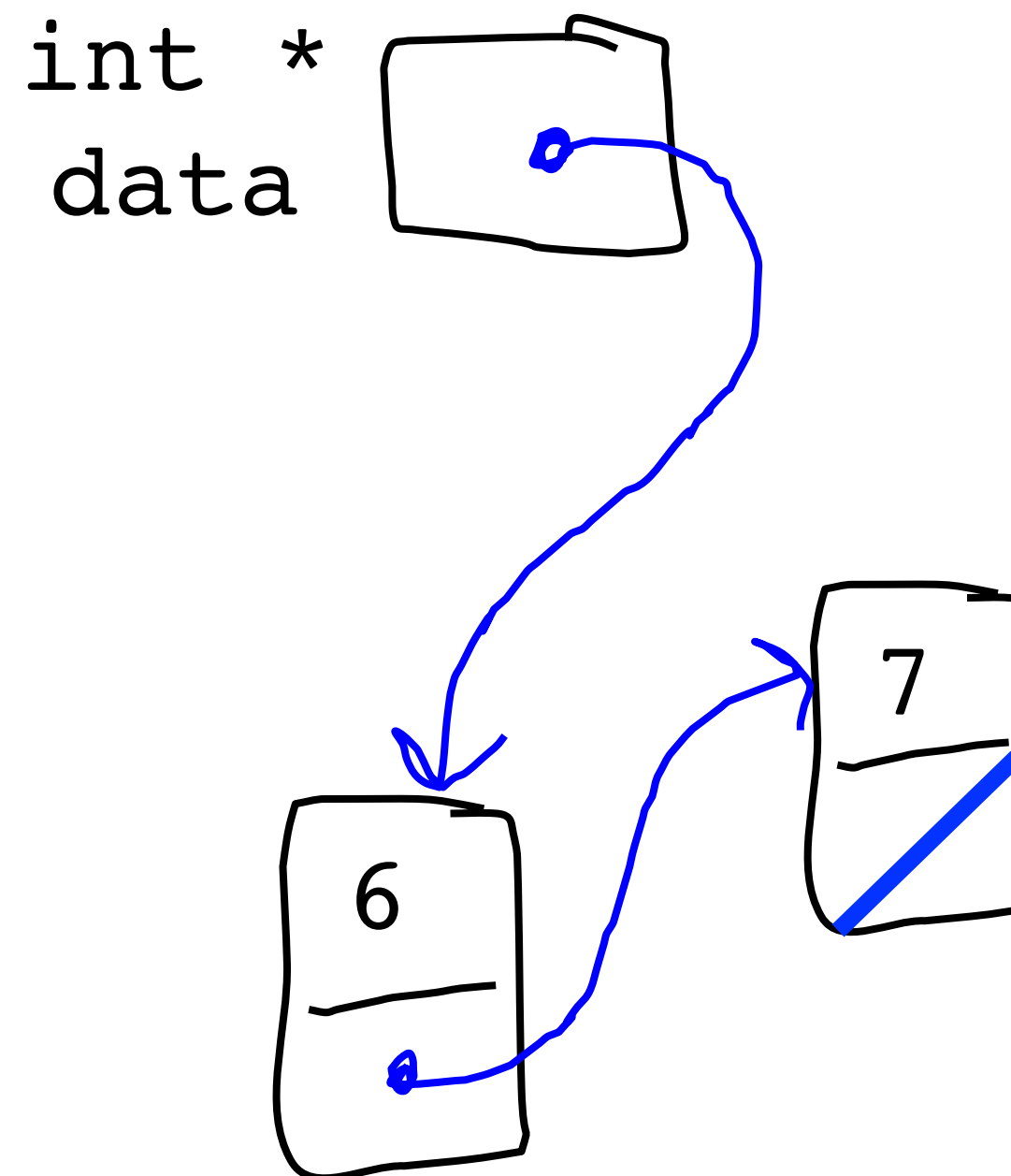
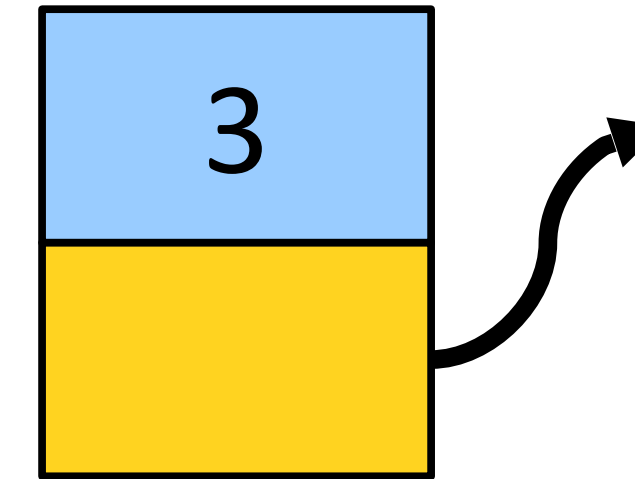


Now we have a way to add
to the front in $O(1)$ time!



Linked List

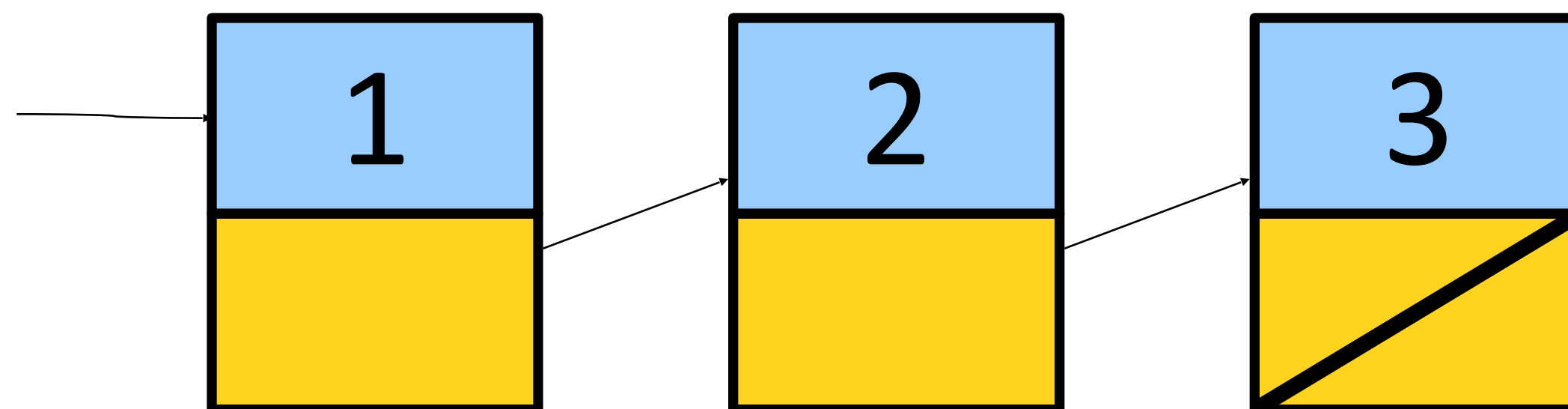
- A linked list is a chain of **nodes**.
- Each node contains two pieces of information:
 - Some piece of data that is stored in the sequence
 - A **link** to the next node in the list.
- We can traverse the list by starting at the first cell and repeatedly following its link.



Linked Lists

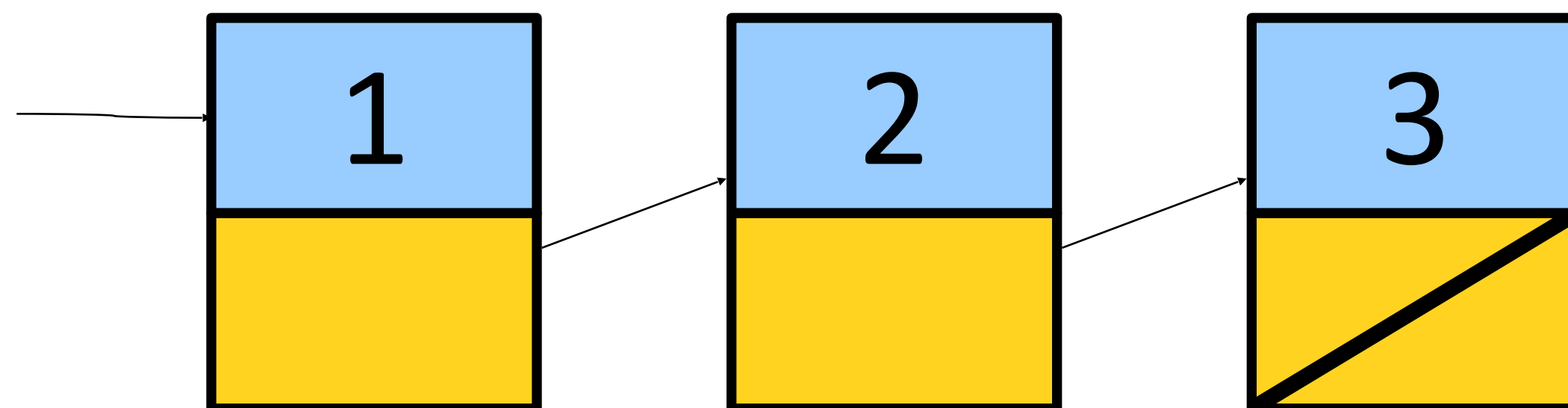


- A **linked list** is a data structure for storing a sequence of elements.
- Each element is stored separately from the rest.
- The elements are then chained together into a sequence.



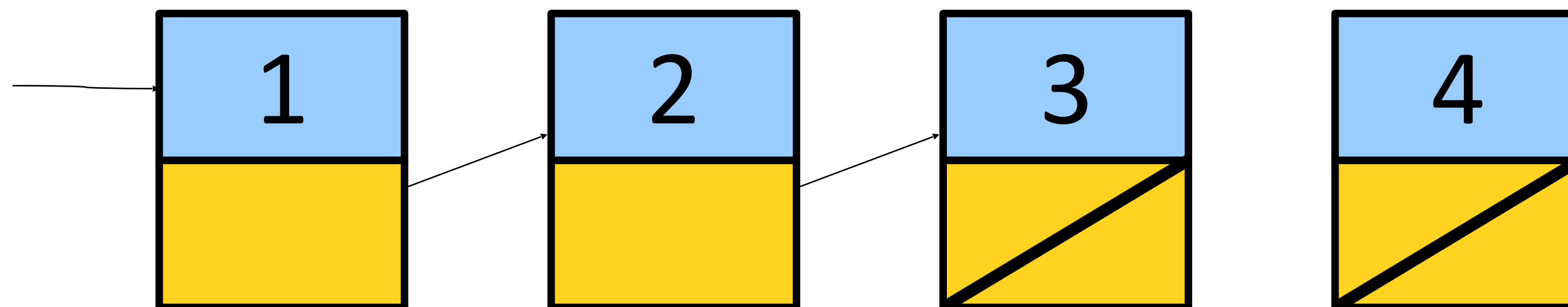
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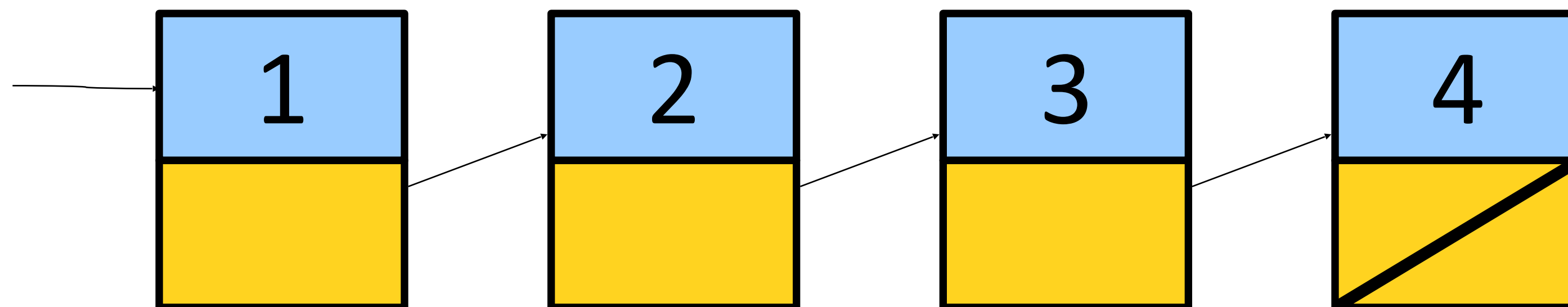
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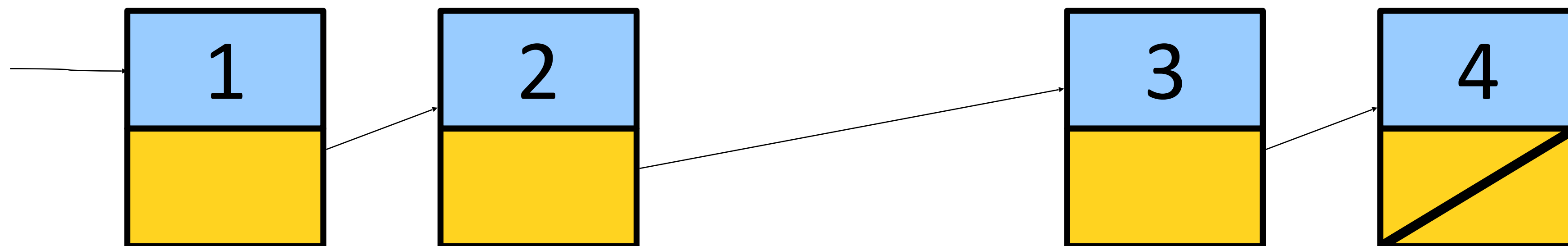
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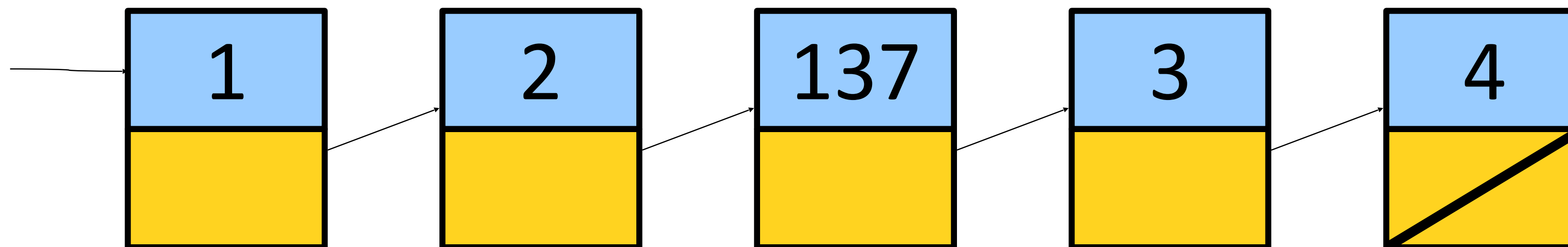
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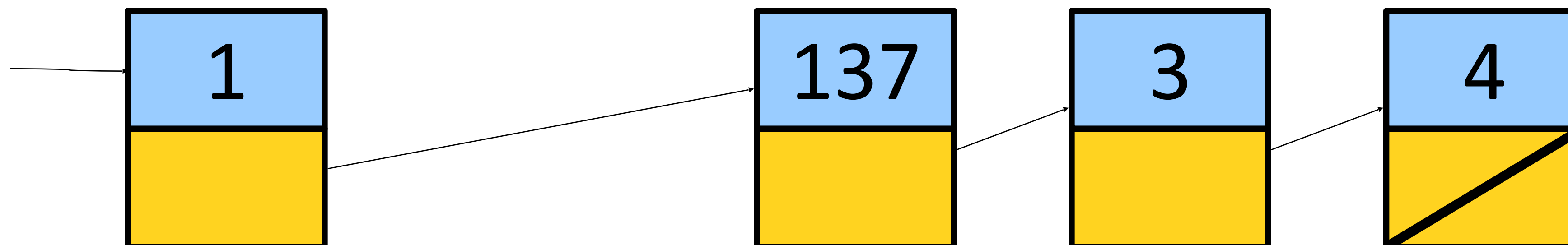
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Why Linked Lists?

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

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



Linked List of Strings

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- The structure is defined recursively!



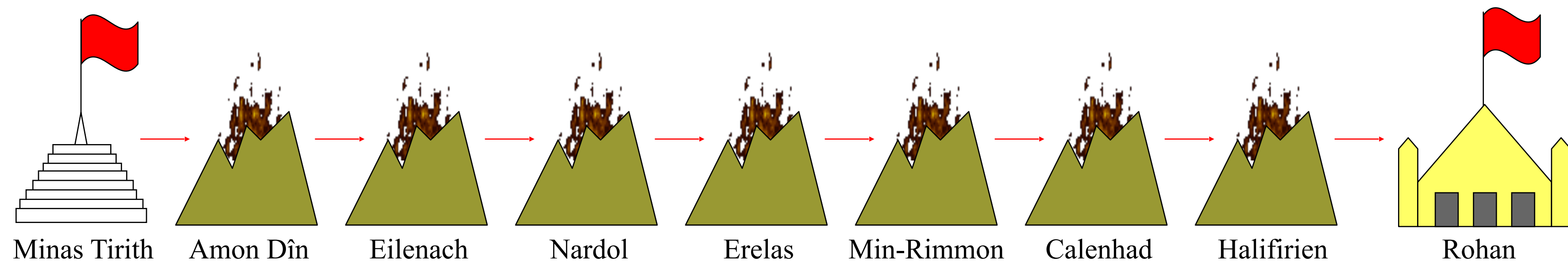
Always!


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.





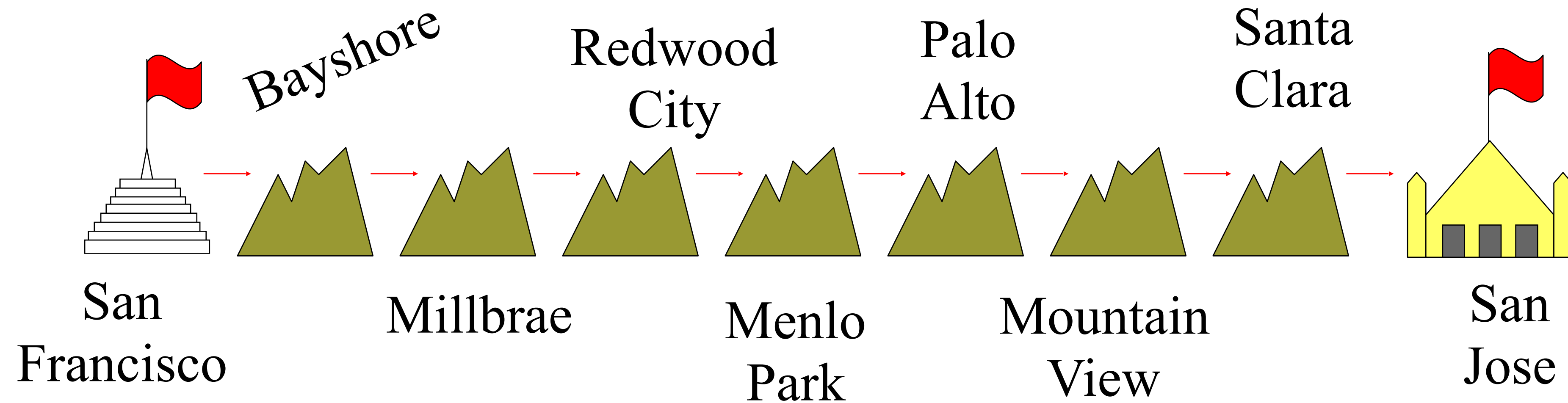
THE
LORD OF THE RINGS
THE RETURN OF THE KING



<https://www.youtube.com/watch?v=i6LGJ7evrAg>

Lord of the Linked Lists

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 */  
};
```



Lord of the Linked Lists

```
// add the first tower  
Tower * head = new Tower;  
head->name = "San Jose";  
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Linked List Trace

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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) {
    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);
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Linked List Trace

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    Tower *tp = new Tower;
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Linked List Trace

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Linked List Trace

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

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

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// main
Tower * head = new Tower;
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```
struct Tower{
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    Tower *tp = new Tower;
    tp->name = name;
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    return tp;
}
```



Linked List Trace

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struct Tower{
    string name;
    Tower * link;
};
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Tower *createTower(string name, Tower *link) {
    Tower *tp = new Tower;
    tp->name = name;
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Linked List Trace

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```
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    Tower *tp = new Tower;
    tp->name = name;
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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;
}
```

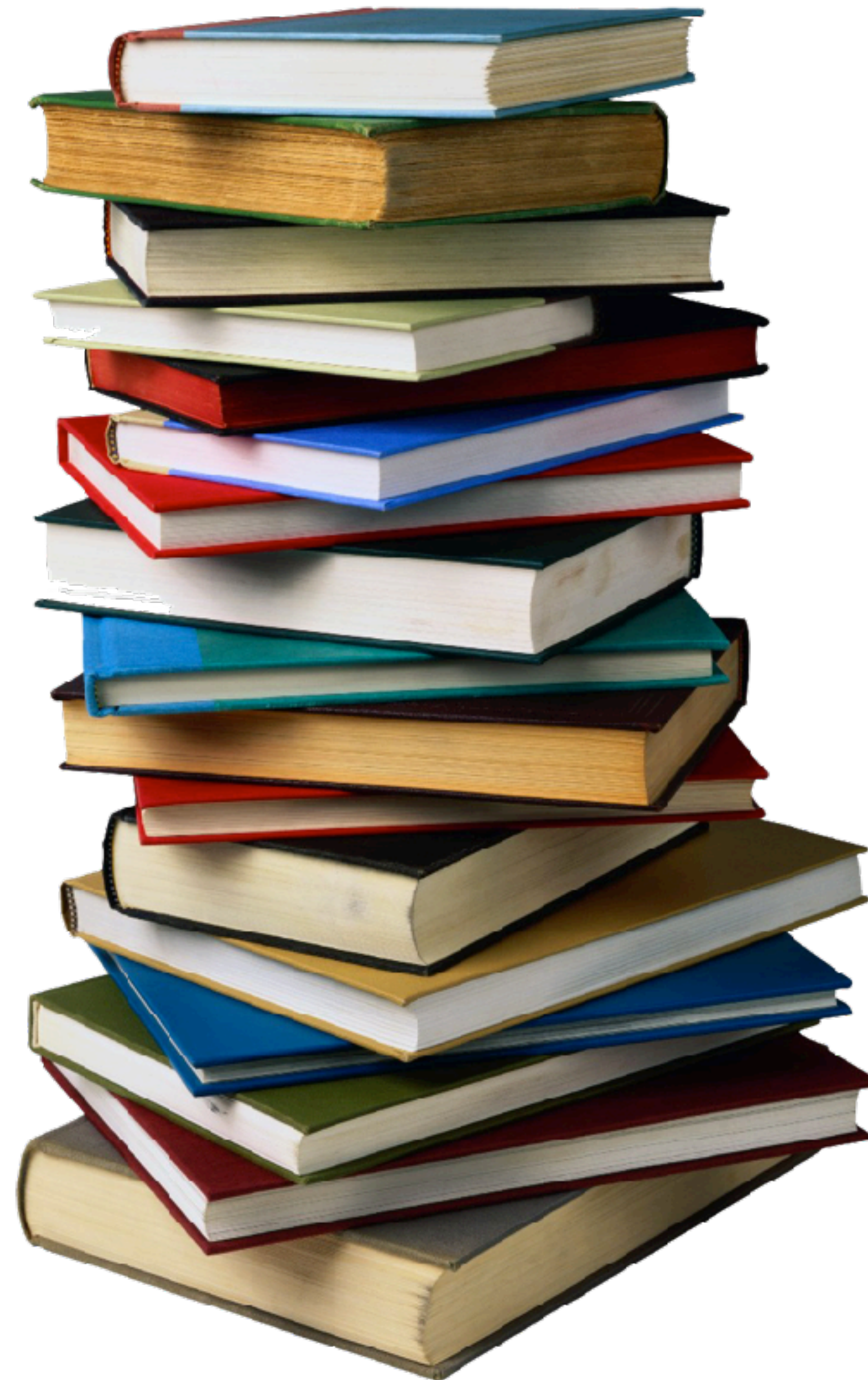


```
void signal(Tower *start) {  
    if (start != NULL) {  
        cout << "Lighting " << start->name << endl;  
        signal(start->link);  
    }  
}
```

```
signal(head);
```

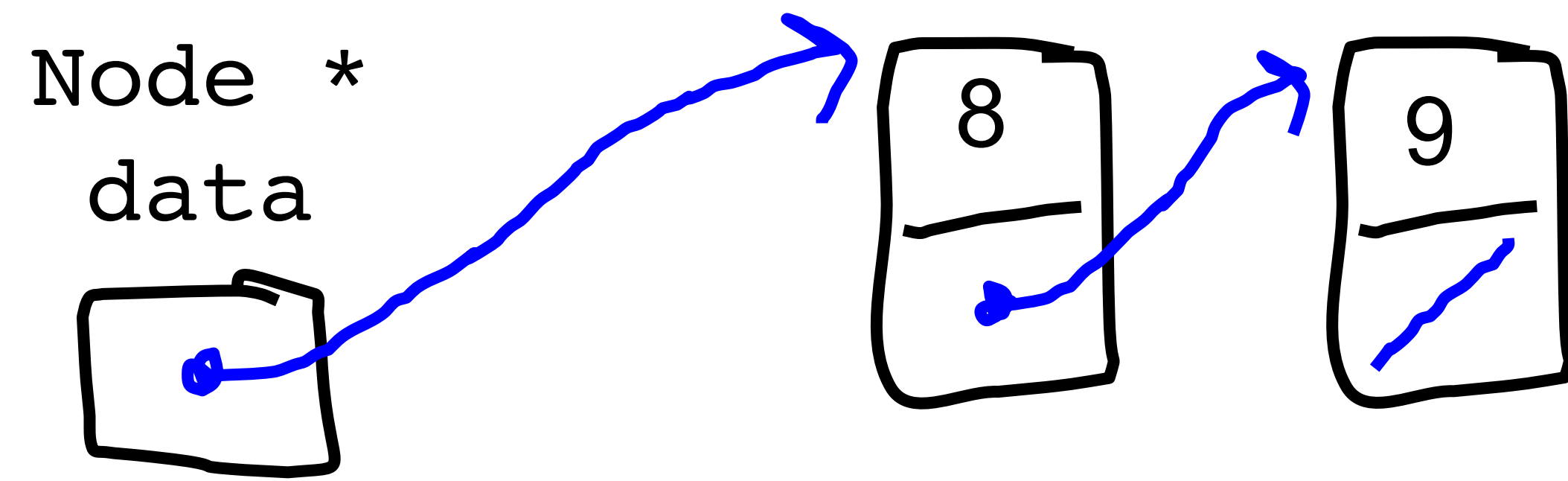


How is the Stack Implemented?



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





Stack

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

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

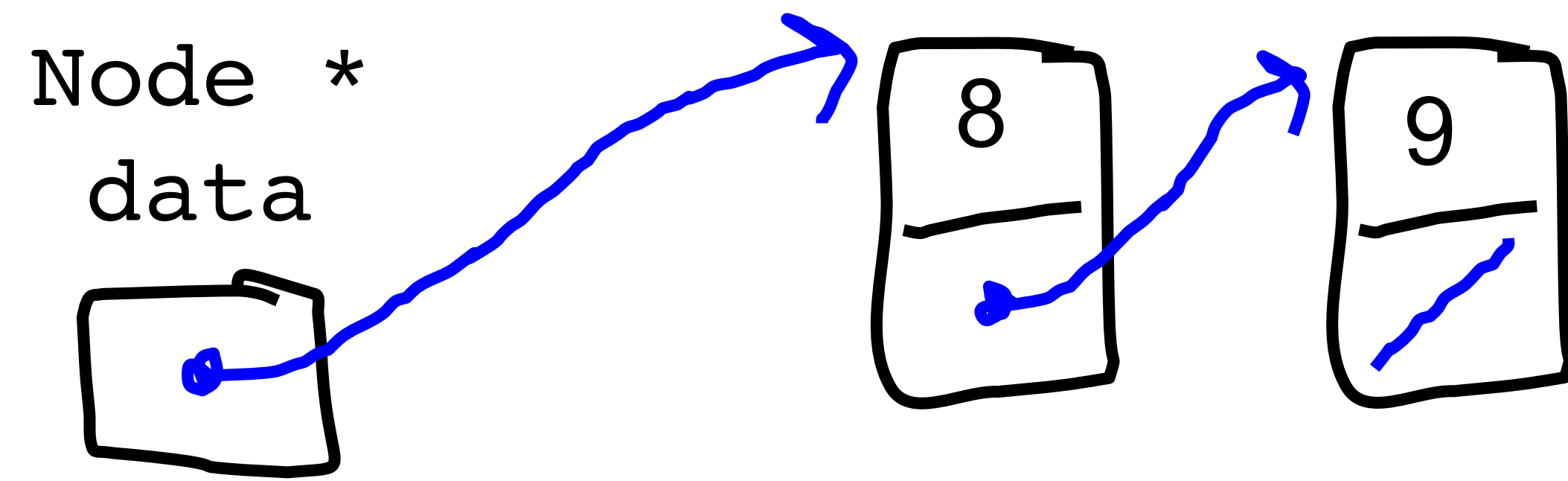
private:
    struct Node {
        int value;
        Node * link;
    };
    Node * data; // member variables
};
```



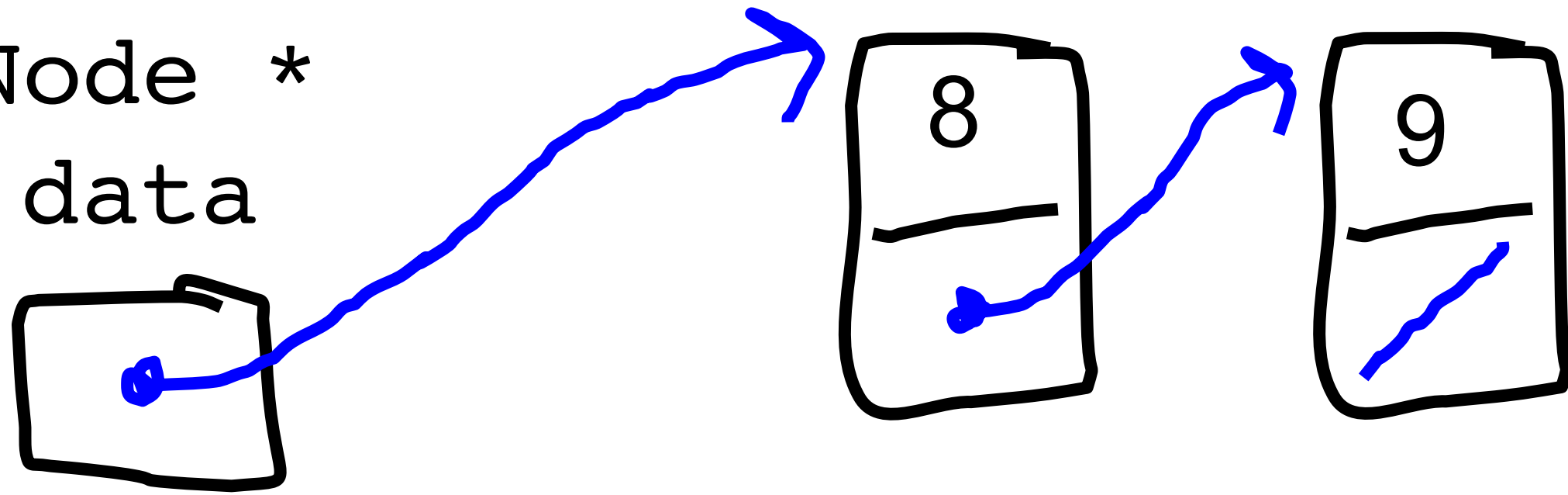
Stack Implementation

```
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 temp;  
    return toReturn;  
}
```





Node *
data

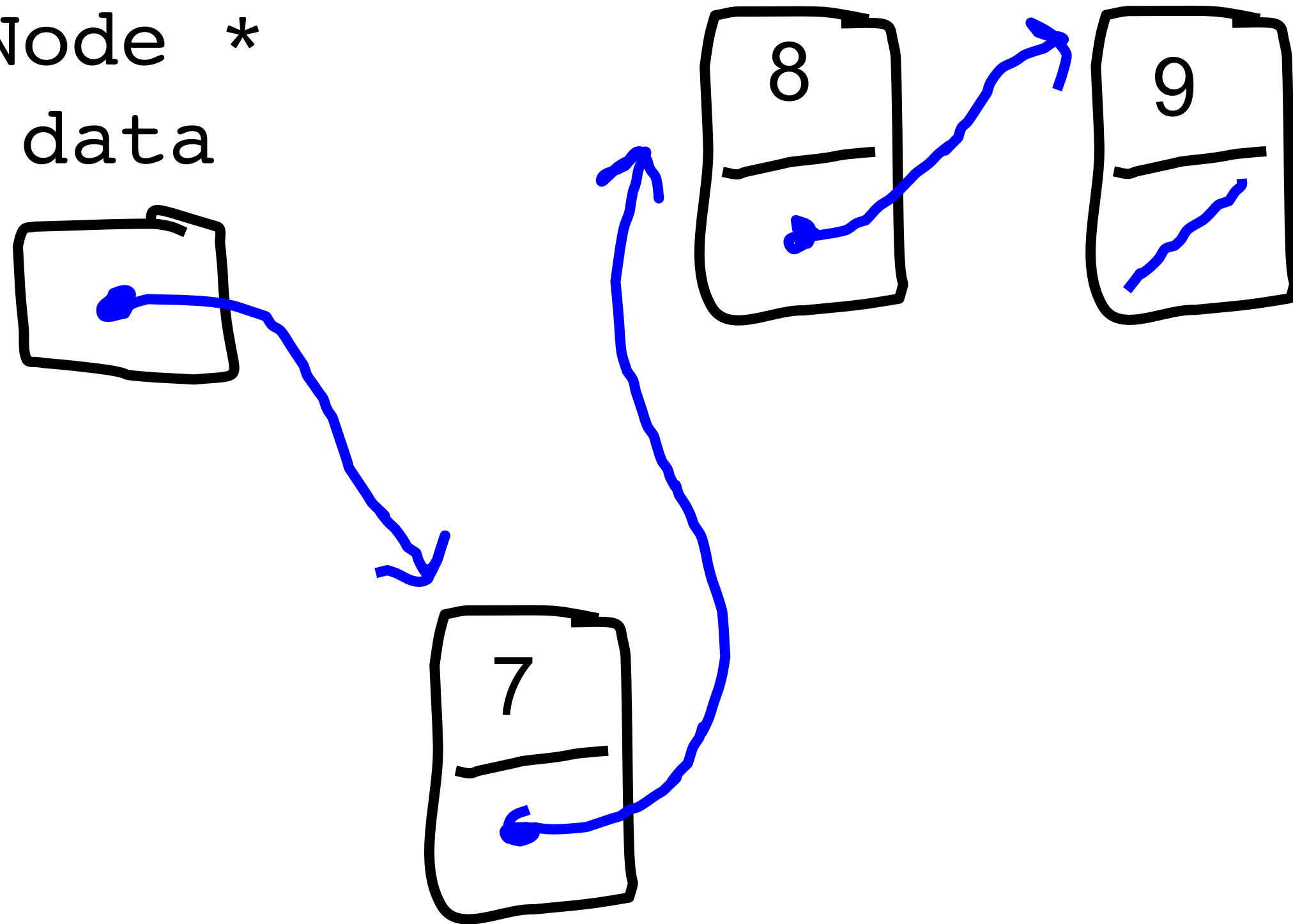


```
push(7);
```

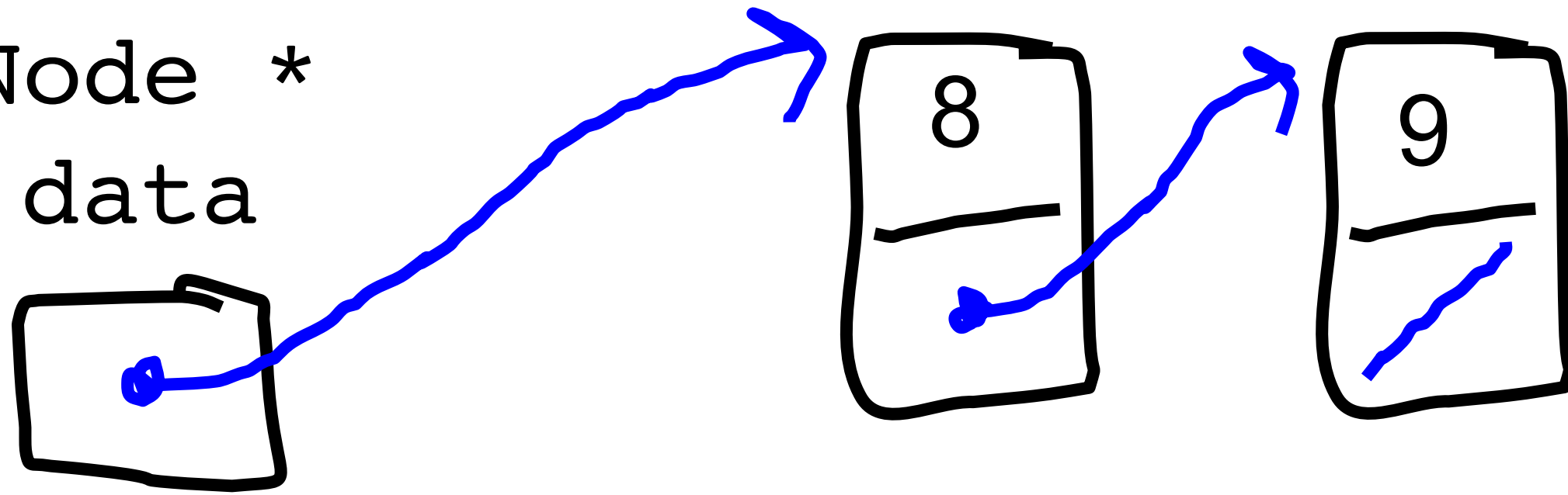


Goal of Push

Node *
data



Node *
data

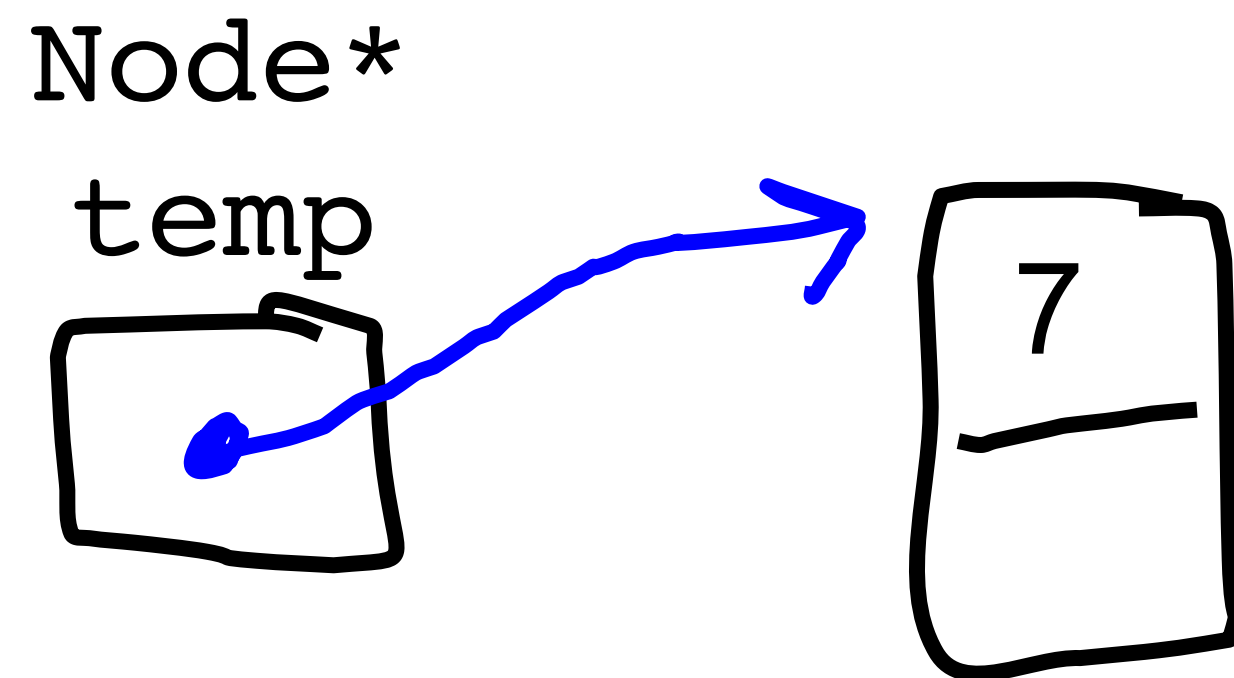
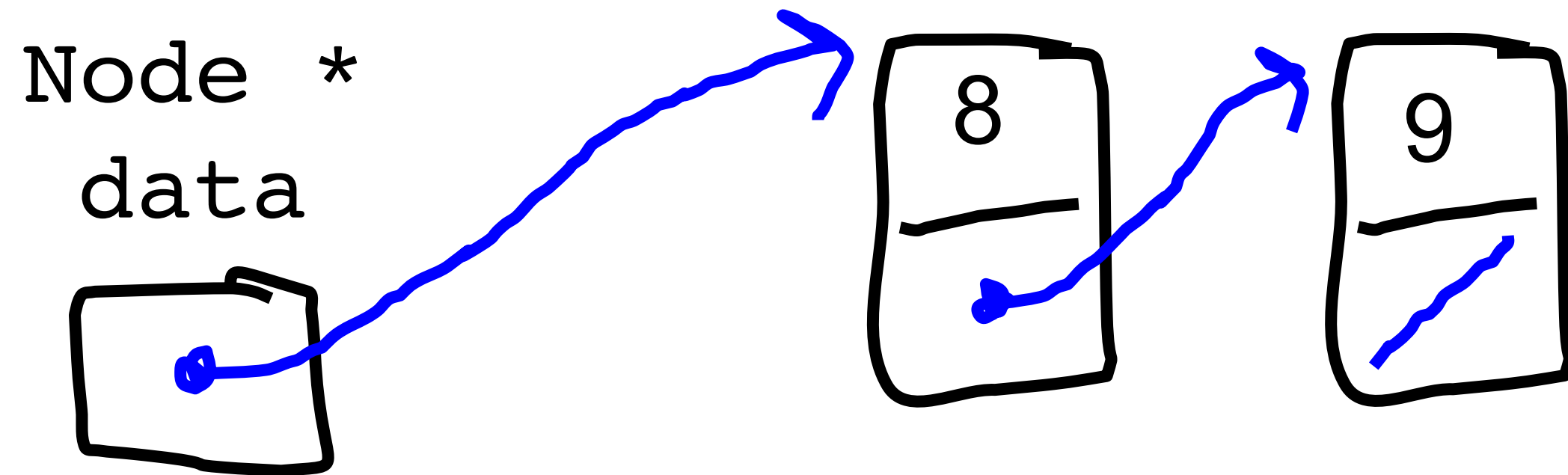


```
push(7);
```



Stack is a Linked List

`push(7);`

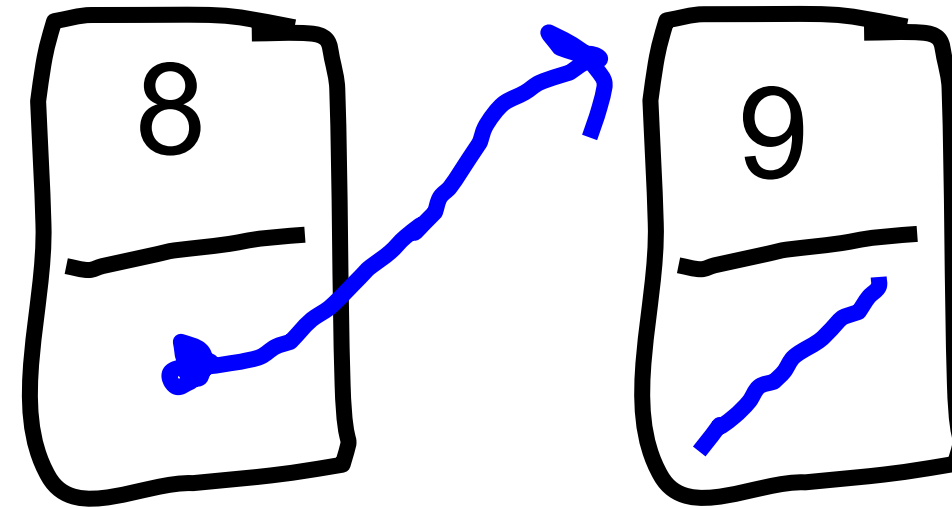
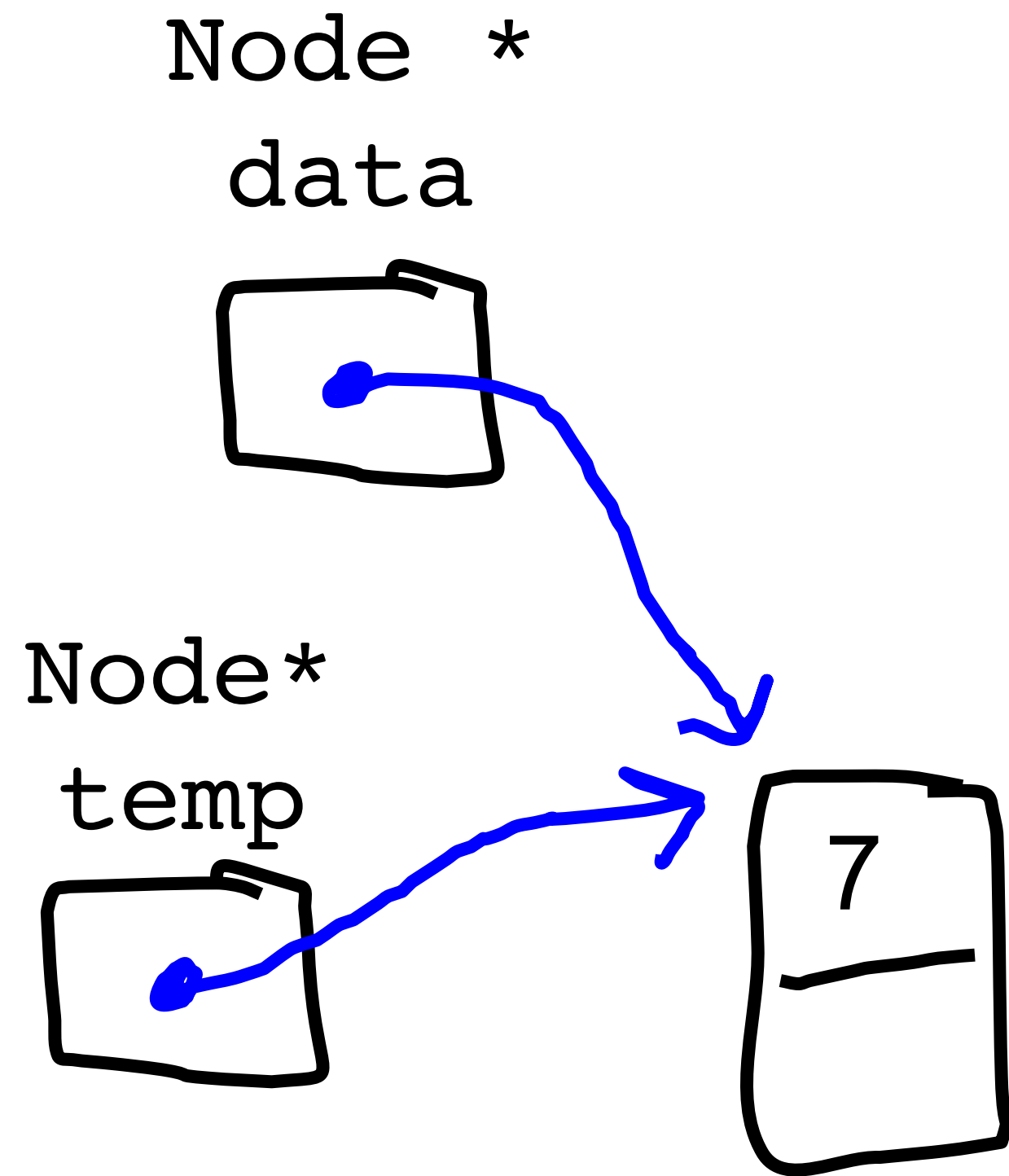


```
Node * temp = new Node;  
temp -> value = 7;
```

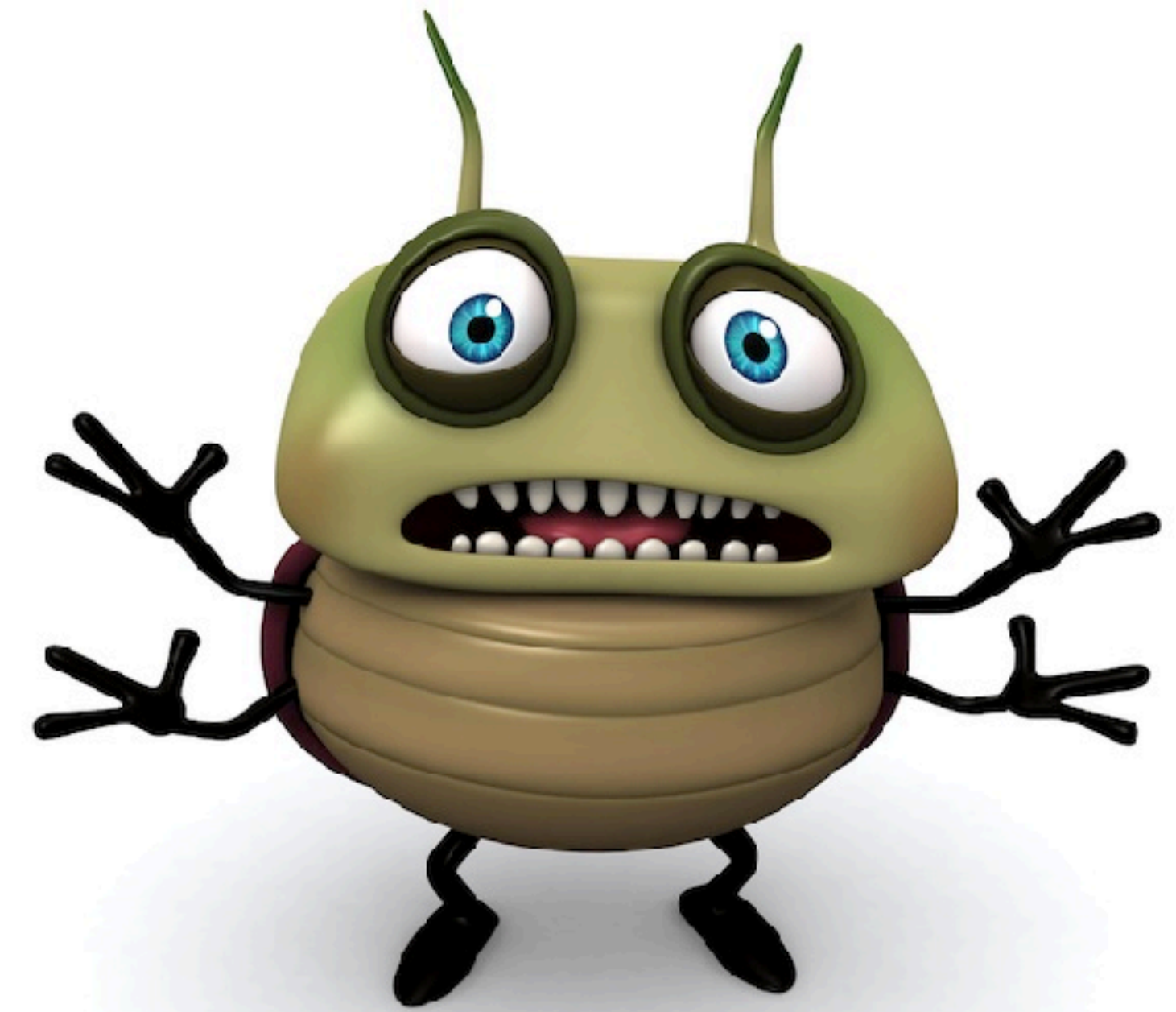


Stack is a Linked List

```
push(7);
```

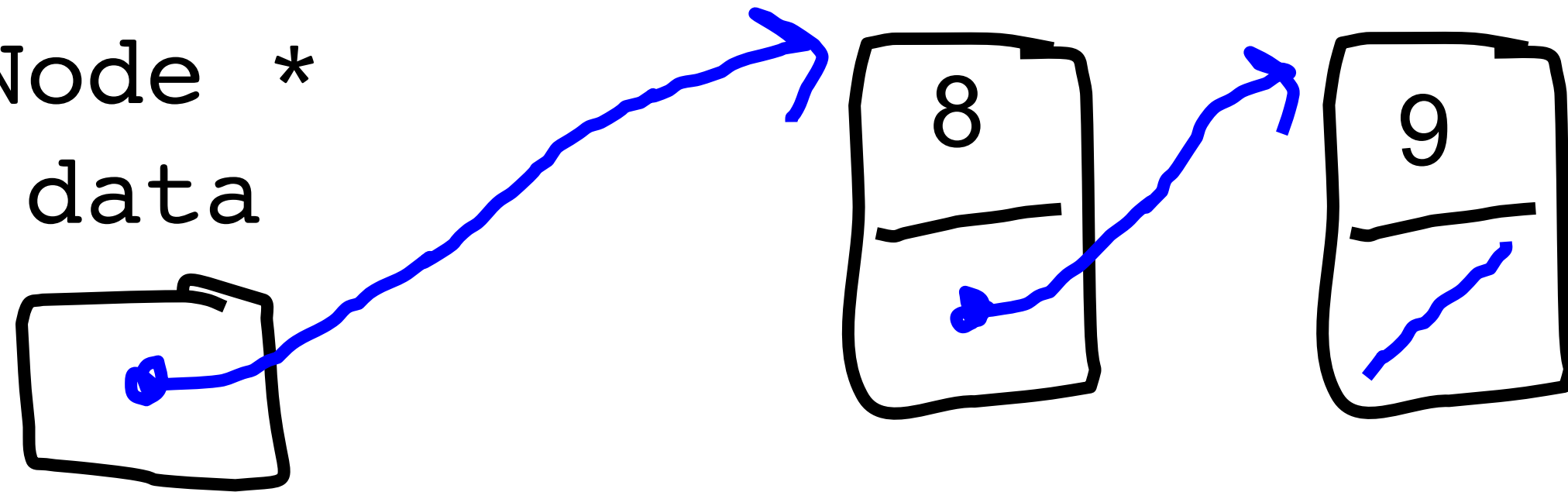


```
data = temp;
```



BRAAWWRRRR!

Node *
data

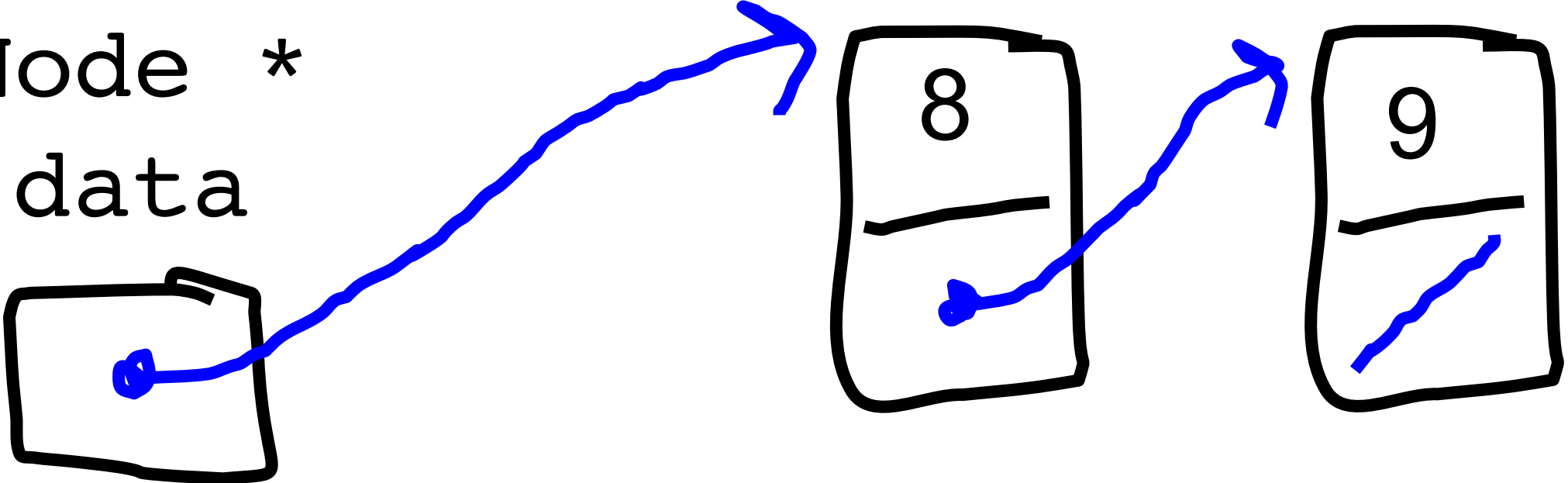


```
push(7);
```

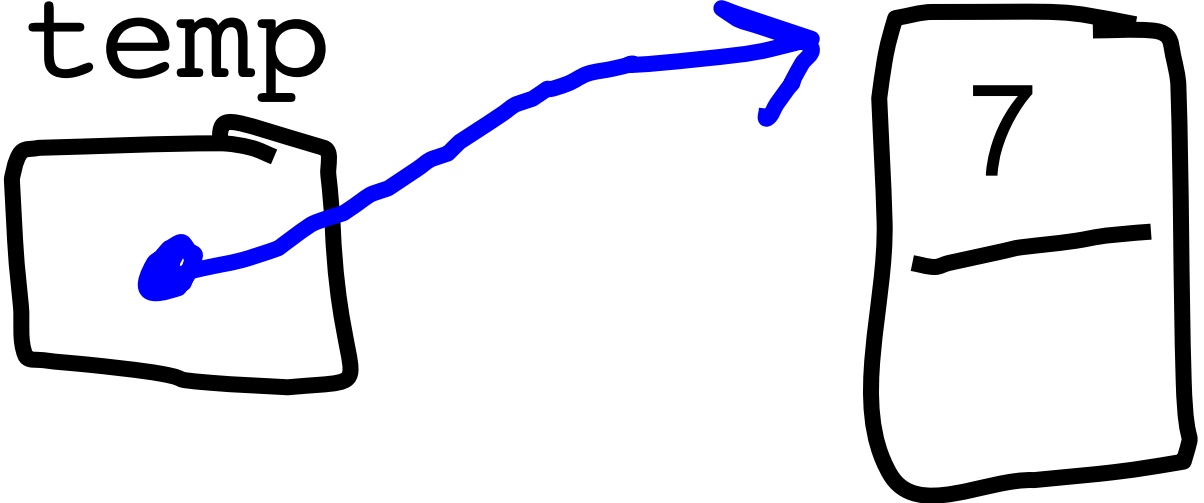


push(7);

Node *
data



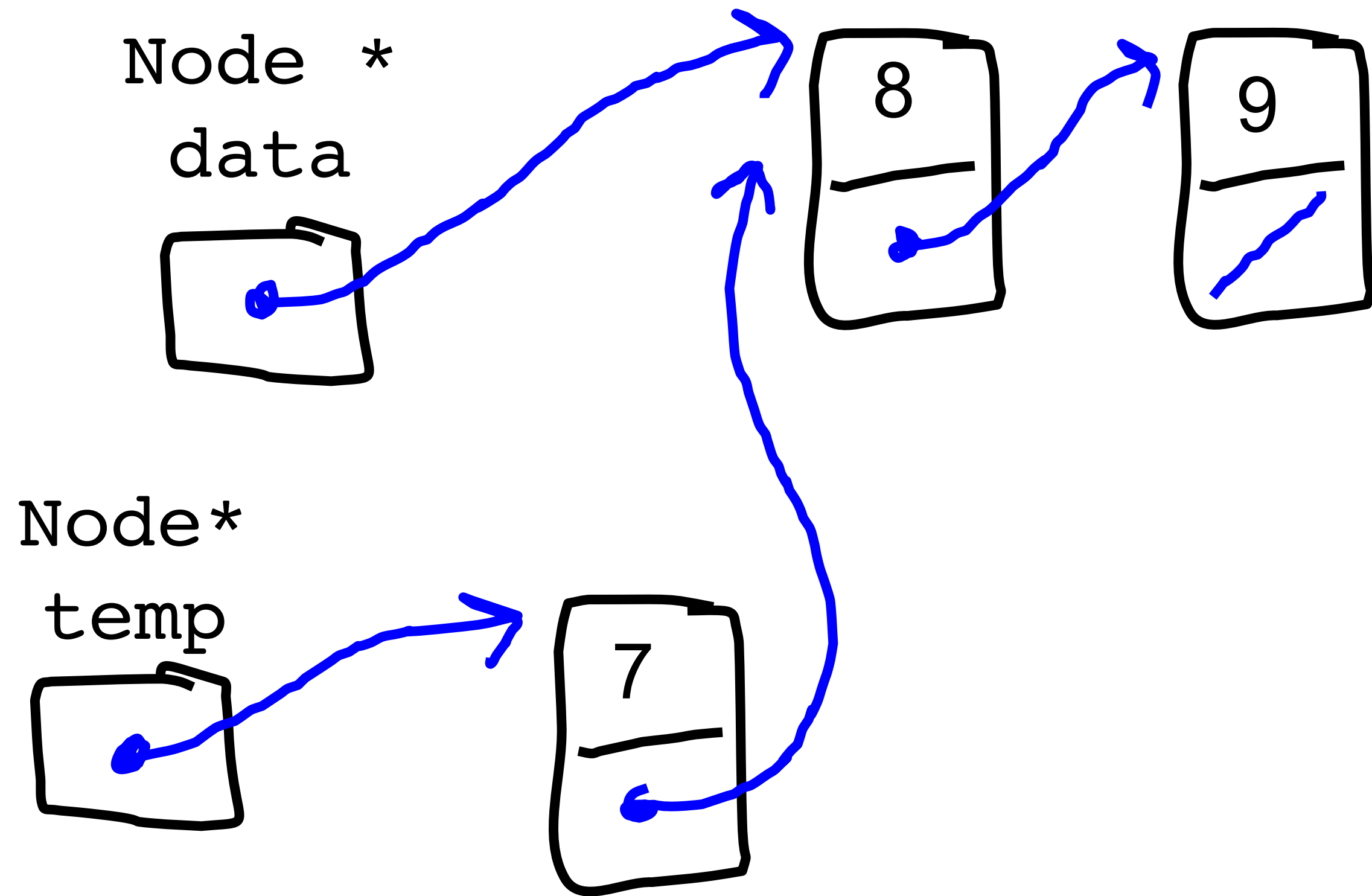
Node*
temp



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



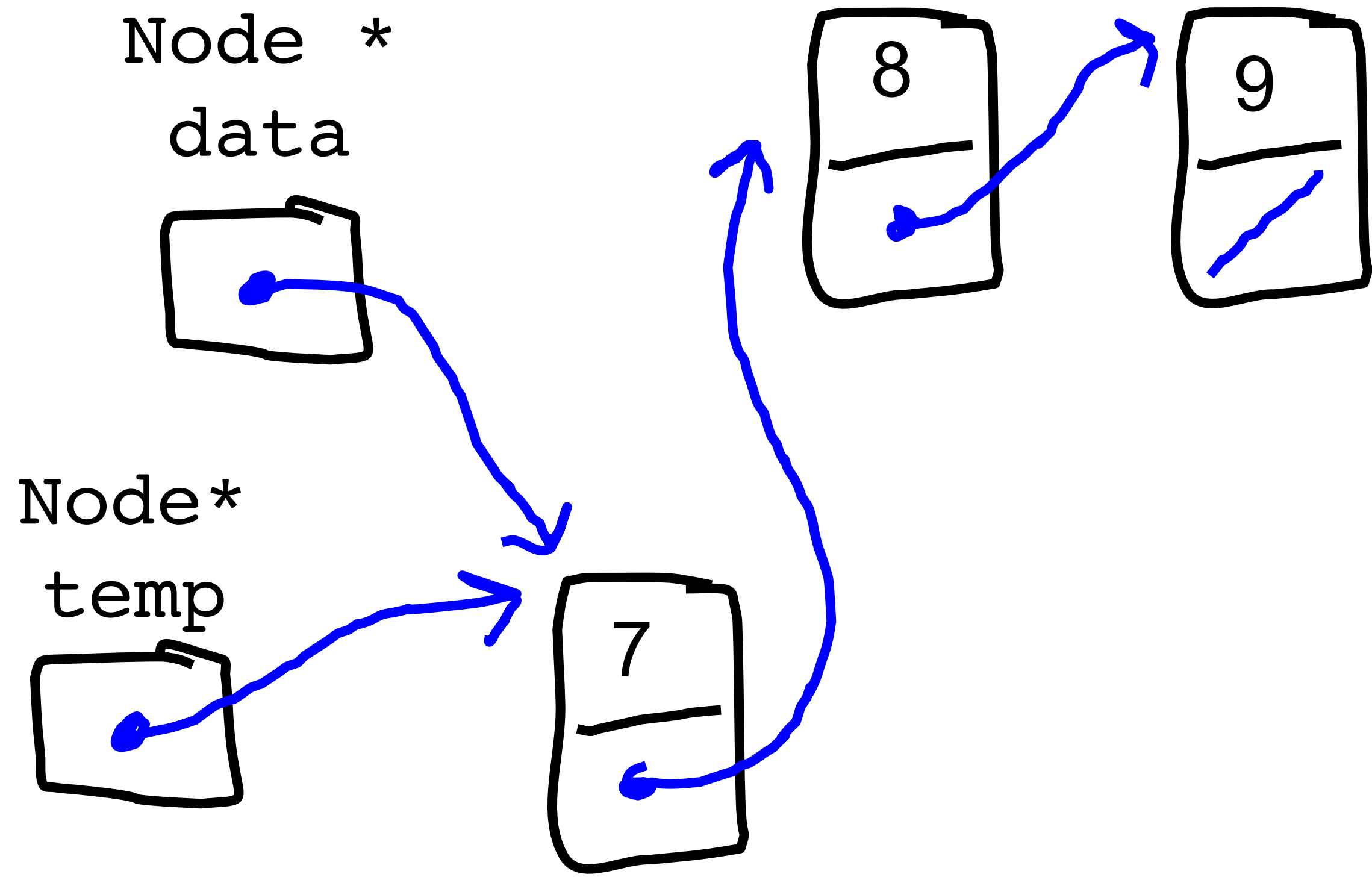
push(7);



temp -> link = data;



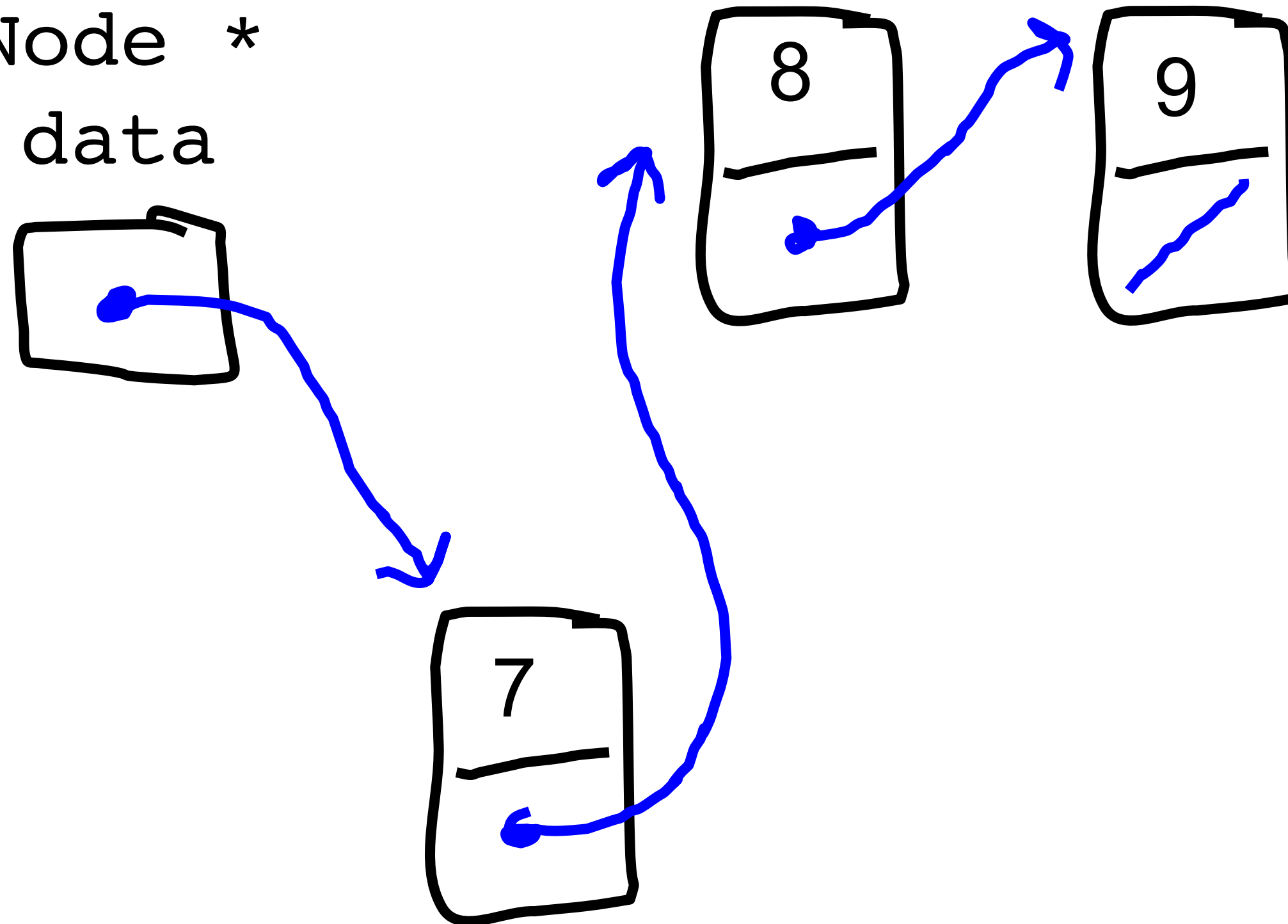
`push(7);`



`data = temp;`



Node *
data



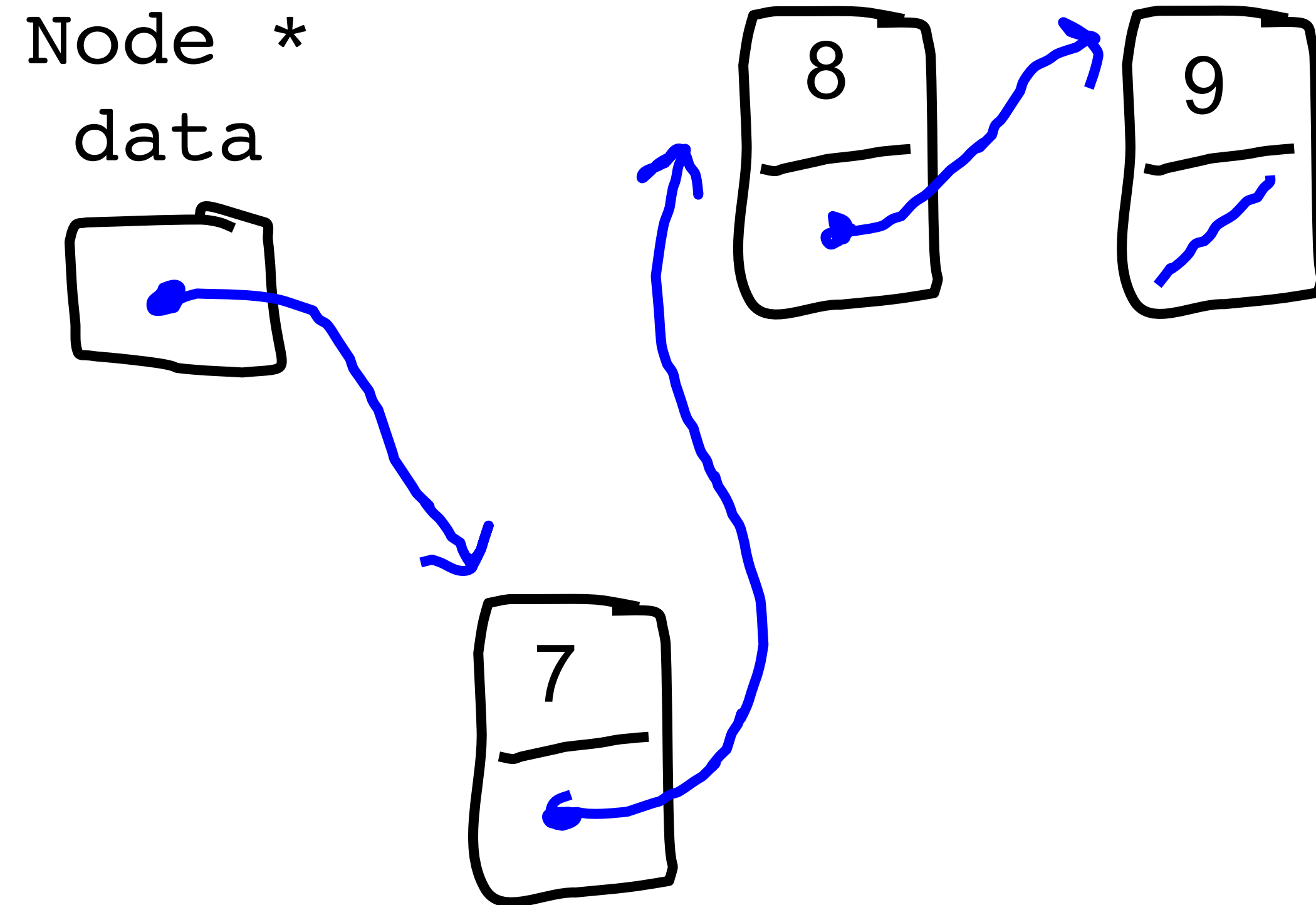
```
push(7);
```

exit function

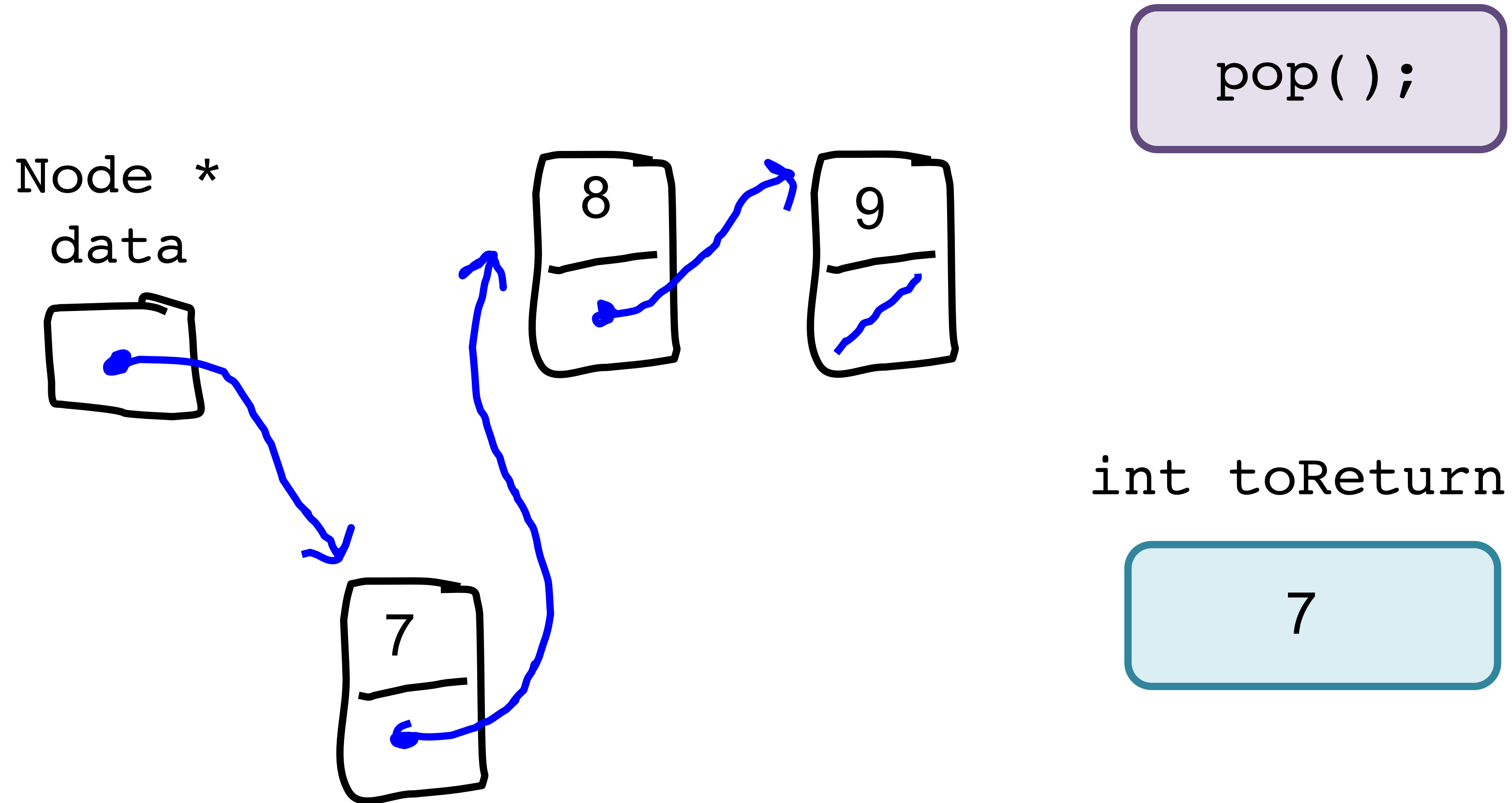


Stack is a Linked List

pop();



Stack is a Linked List

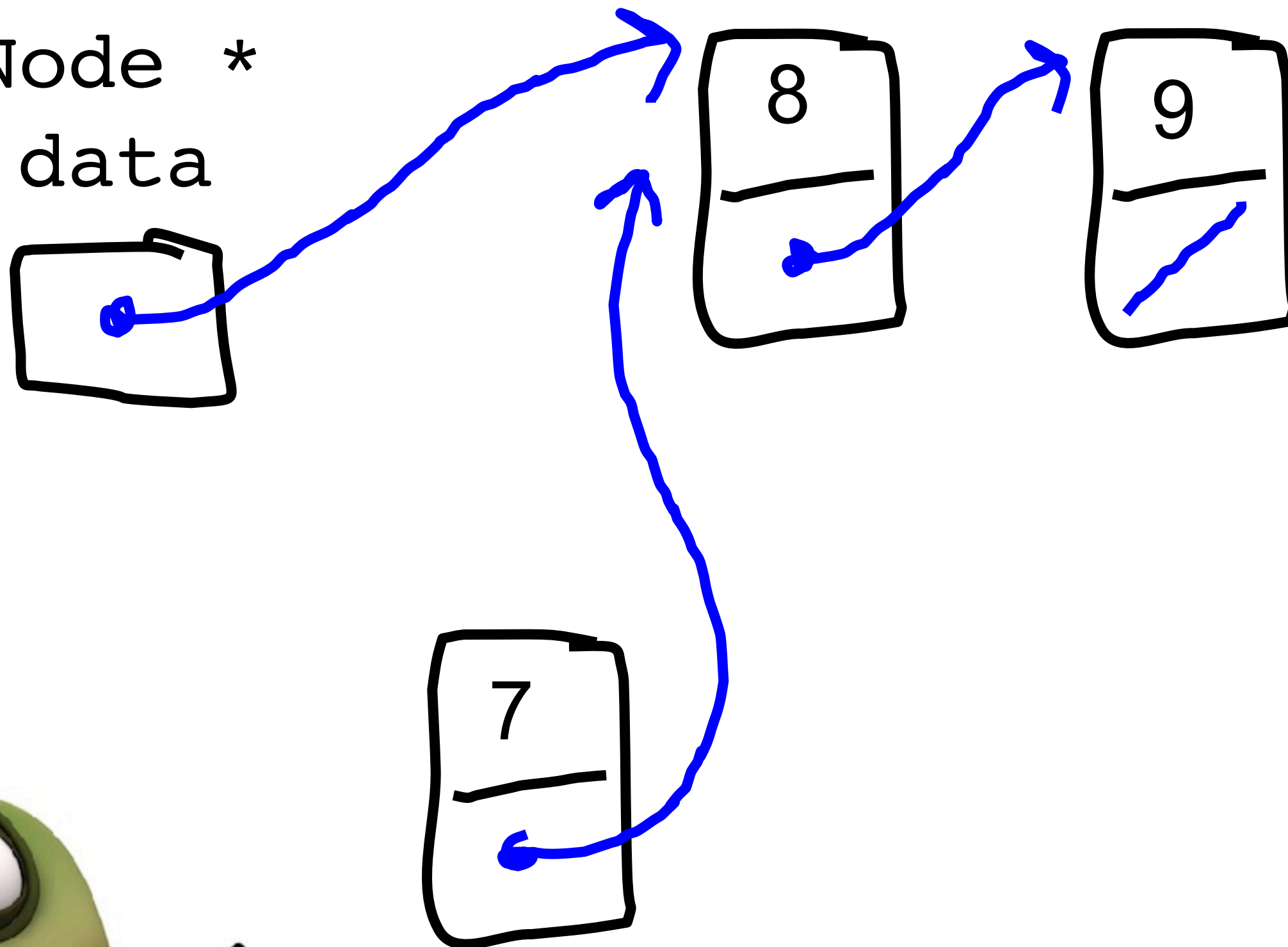


```
int toReturn = data->value;
```



Stack is a Linked List

Node *
data

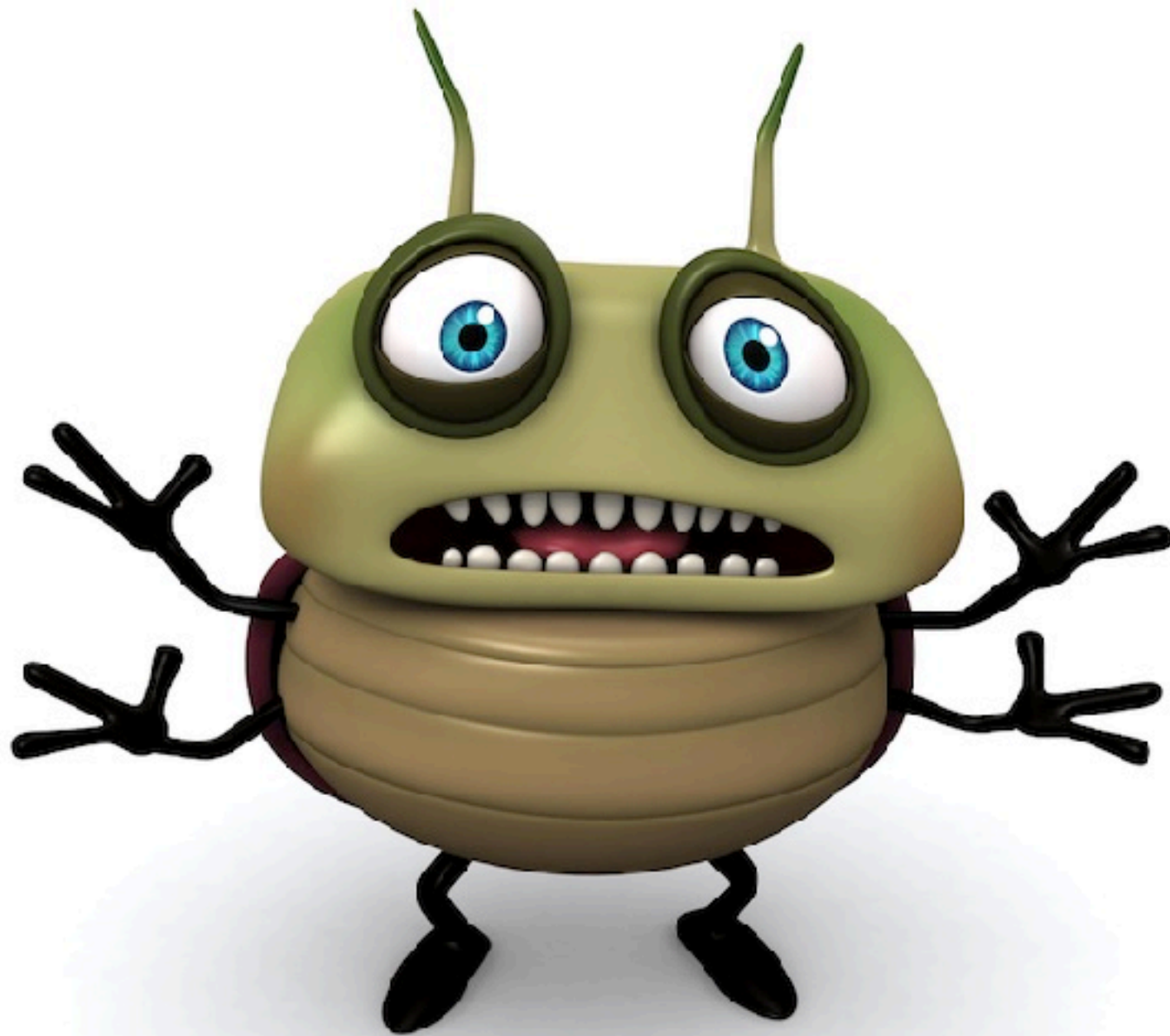


```
pop();
```

int toReturn

```
7
```

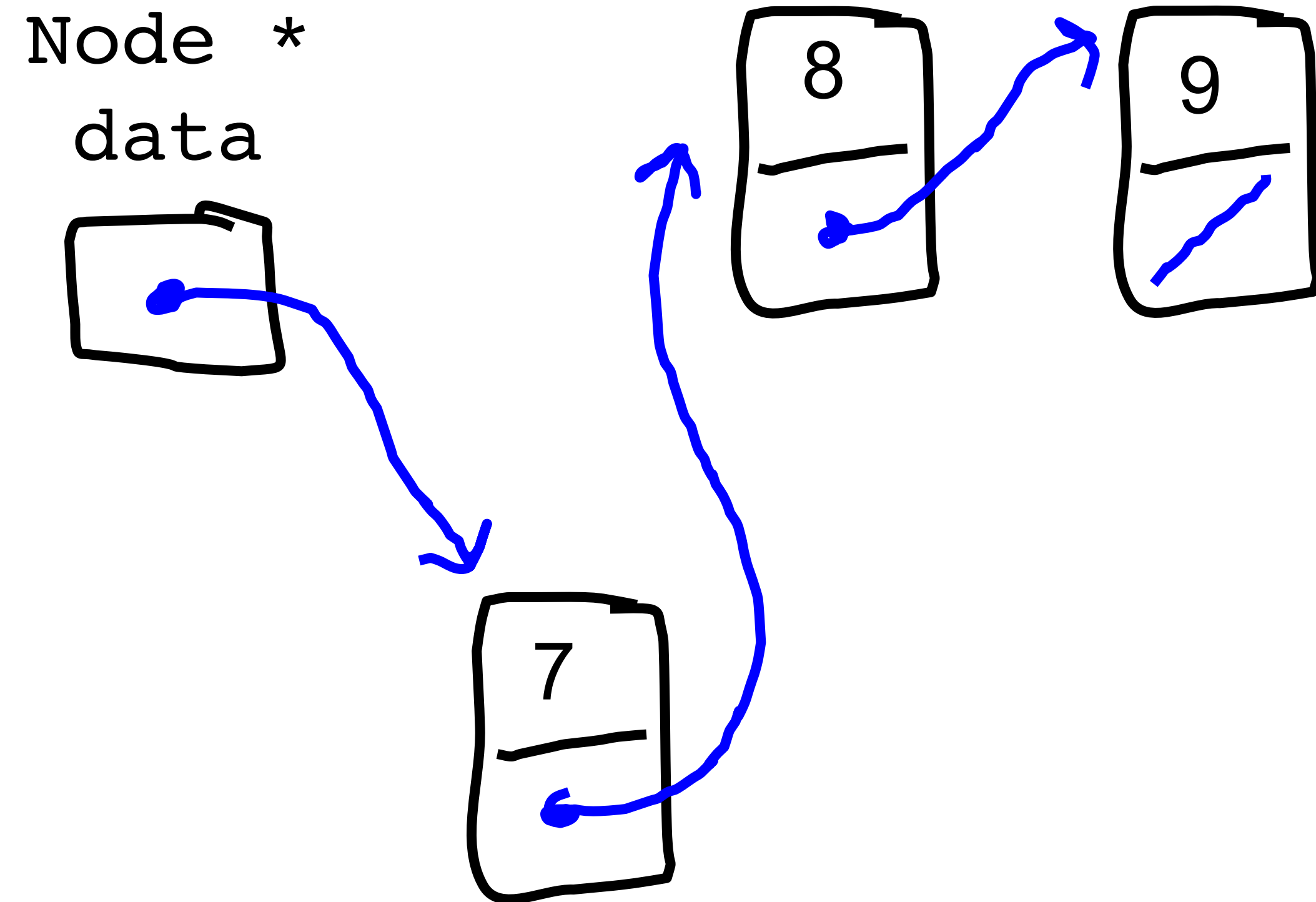
```
data = data->link;
```



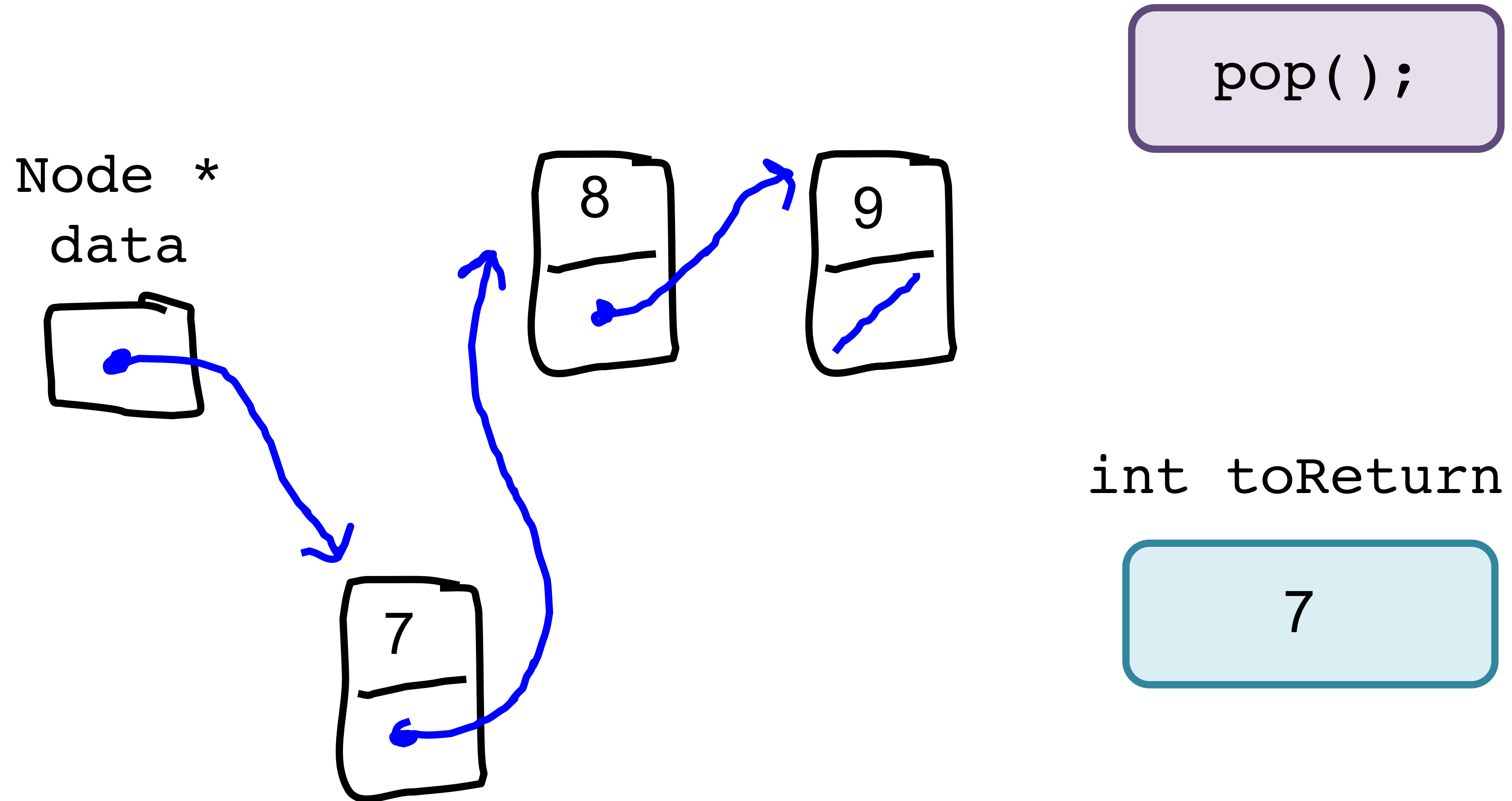
That didn't work. Let's try again...

Stack is a Linked List

pop();



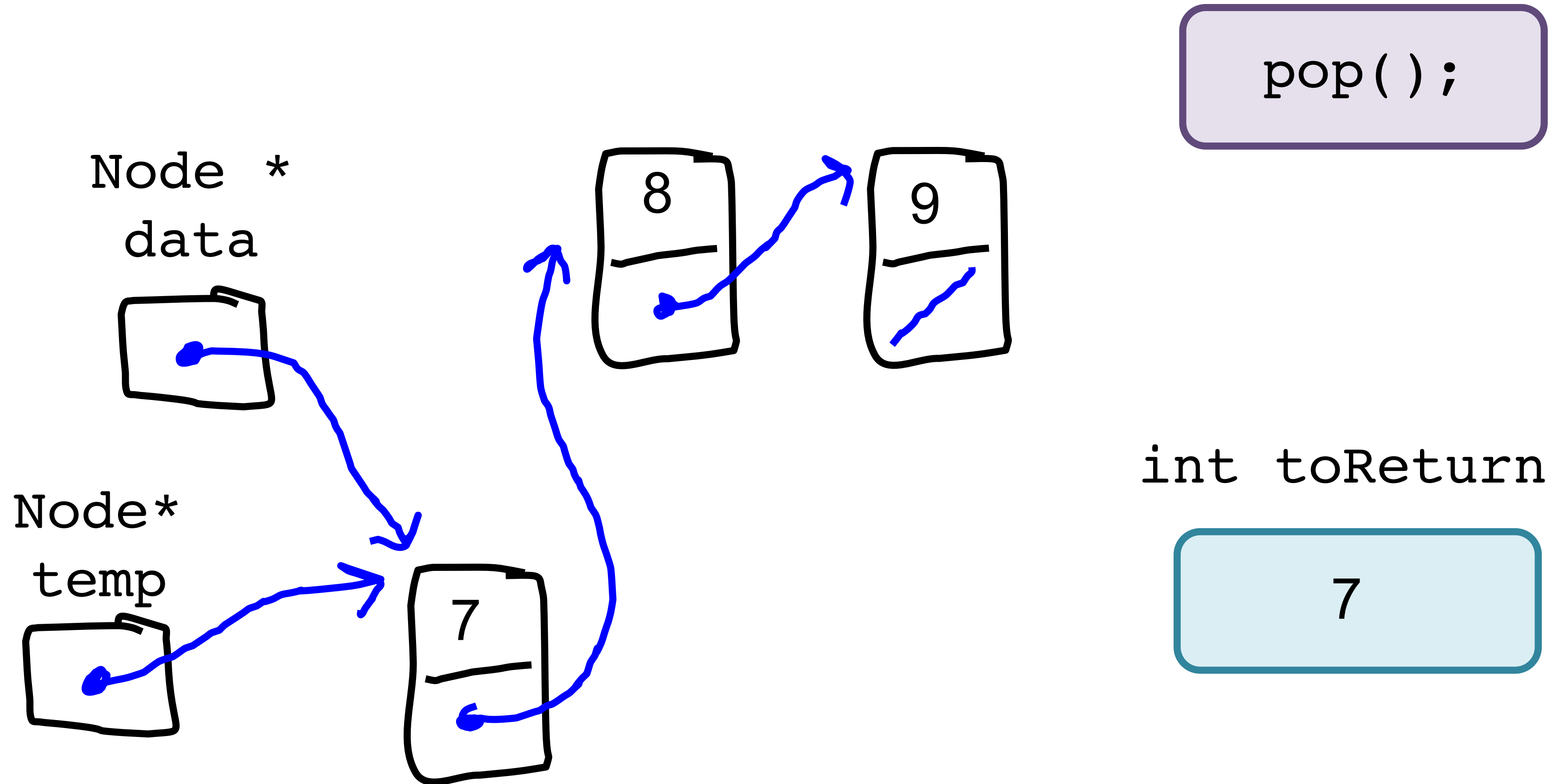
Stack is a Linked List



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



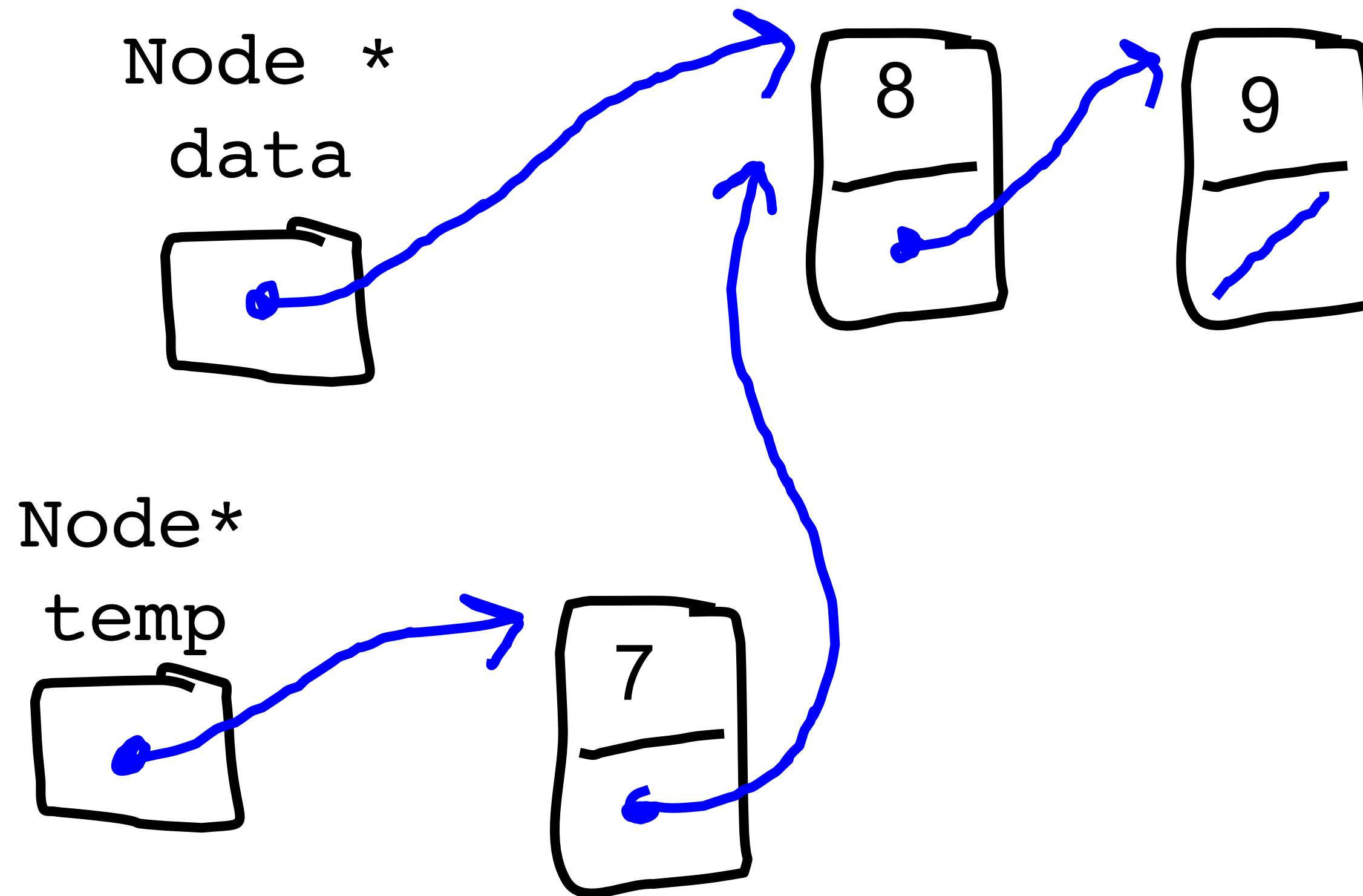
Stack is a Linked List



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



Stack is a Linked List



```
pop();
```

int toReturn

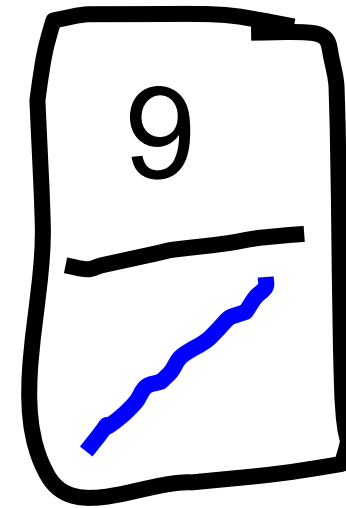
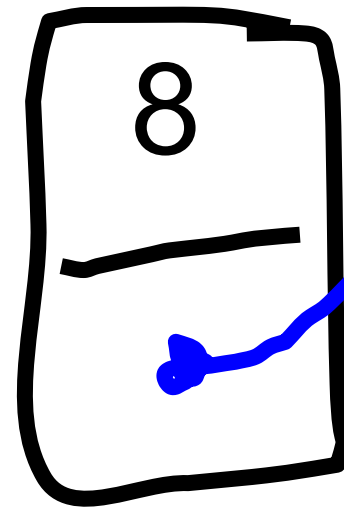
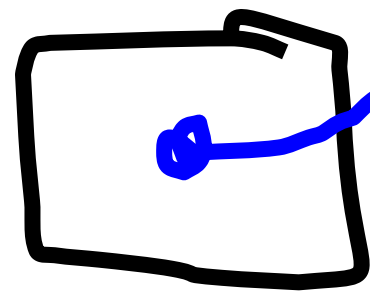
```
7
```

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



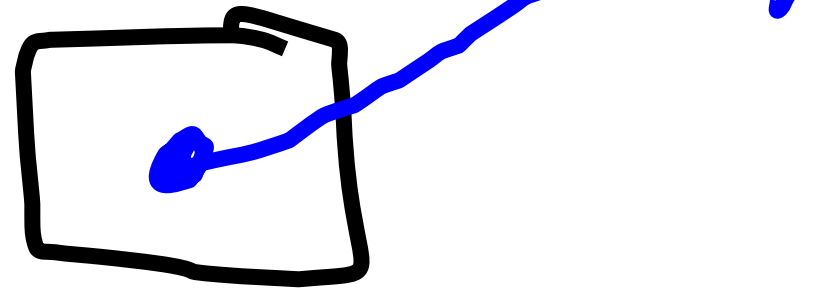
Stack is a Linked List

Node *
data



```
pop();
```

Node*
temp



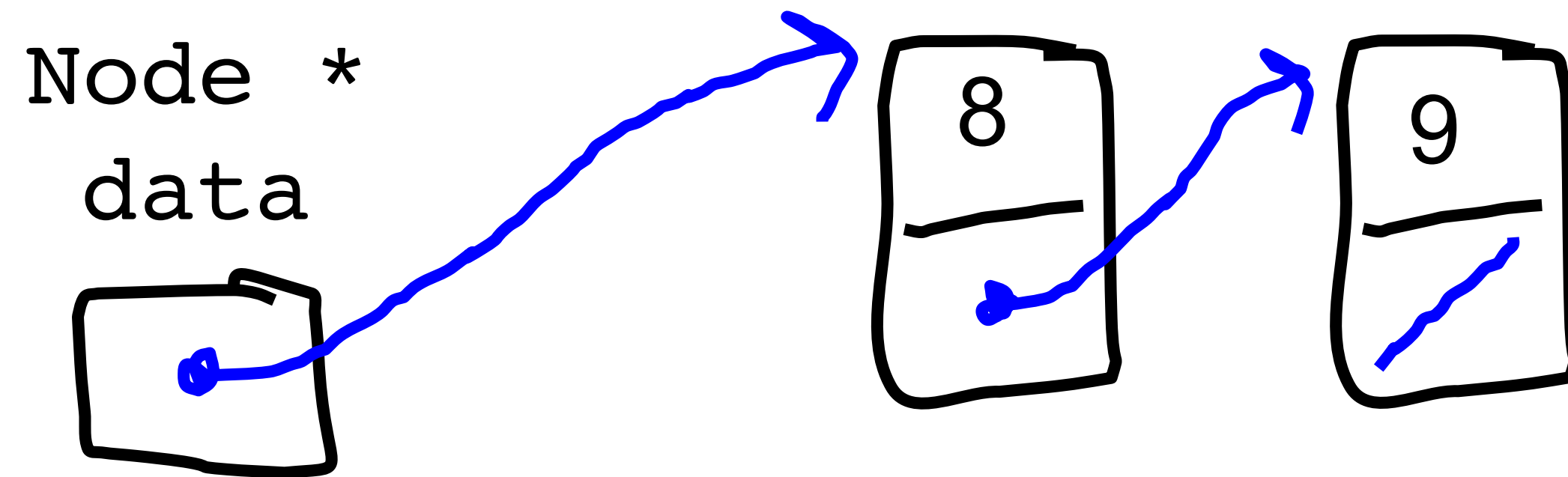
int toReturn

```
7
```

```
delete temp;
```



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 Implementation: Big O?

Big O of `push()`? $O(1)$

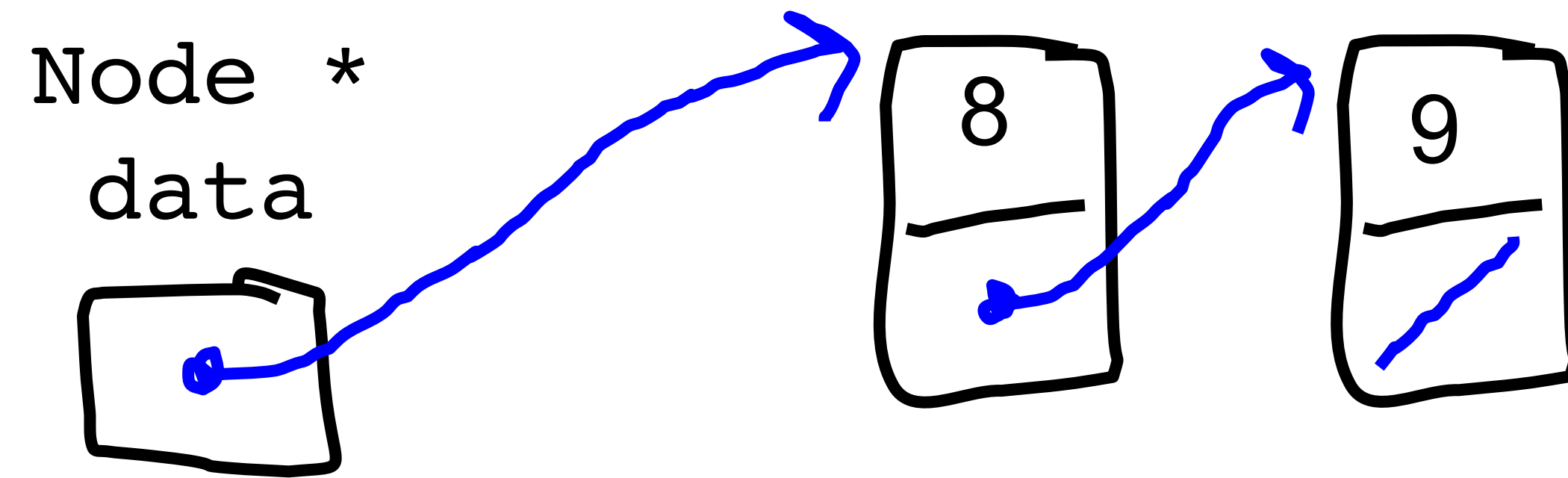
Big O of `pop()`? $O(1)$

Yay!

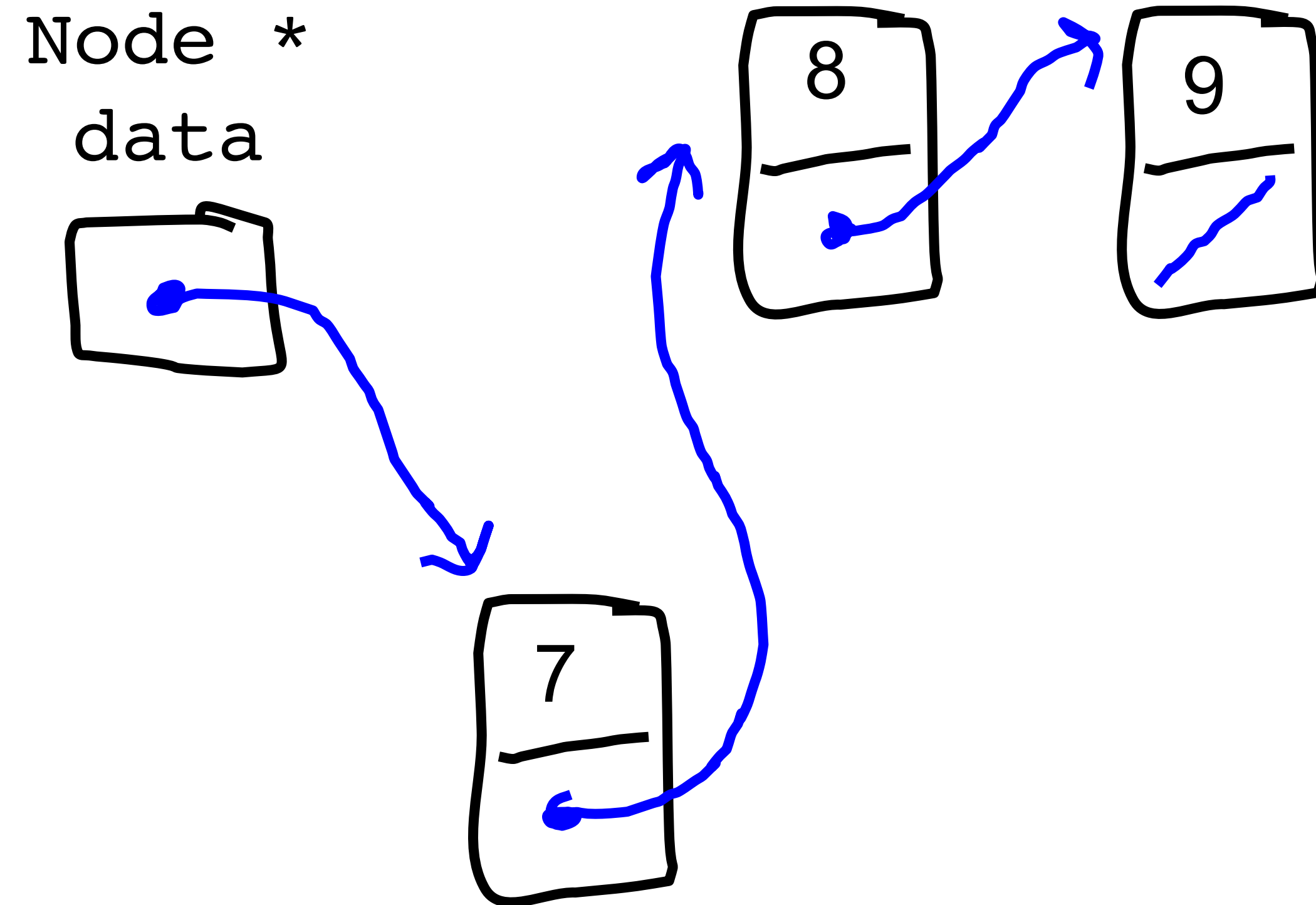




Queue?

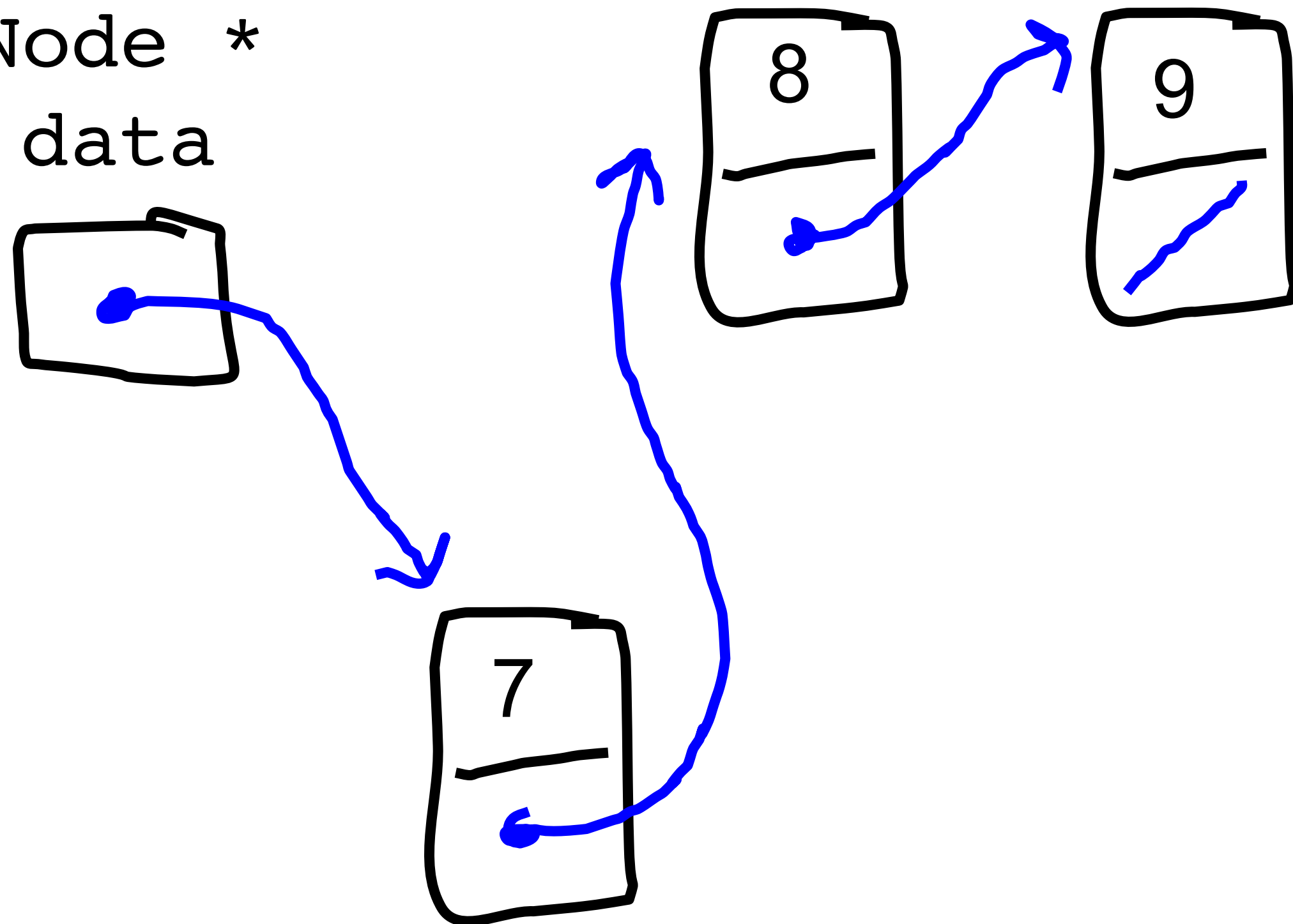


Queue Enqueue?



Queue Enqueue?

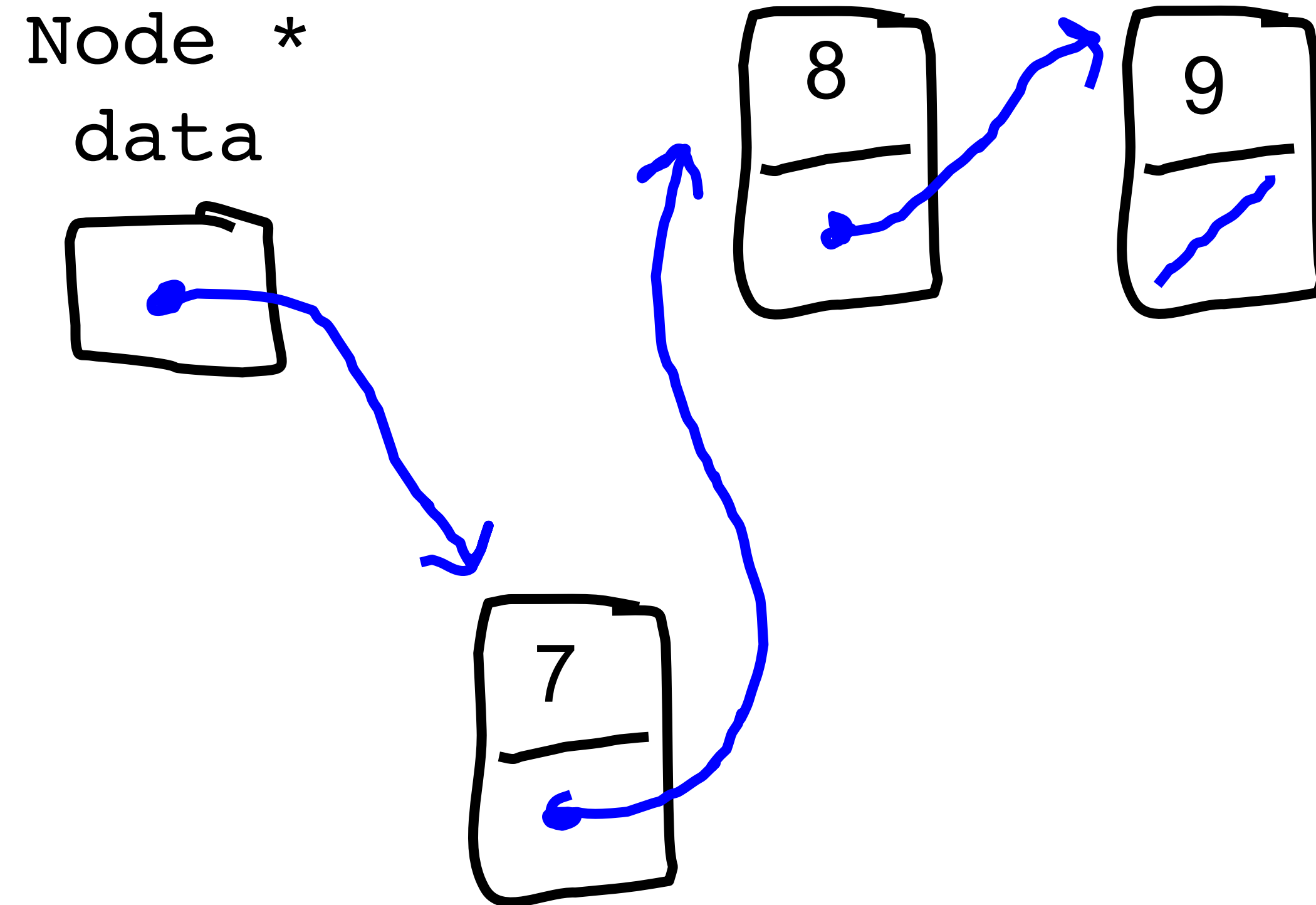
Node *
data



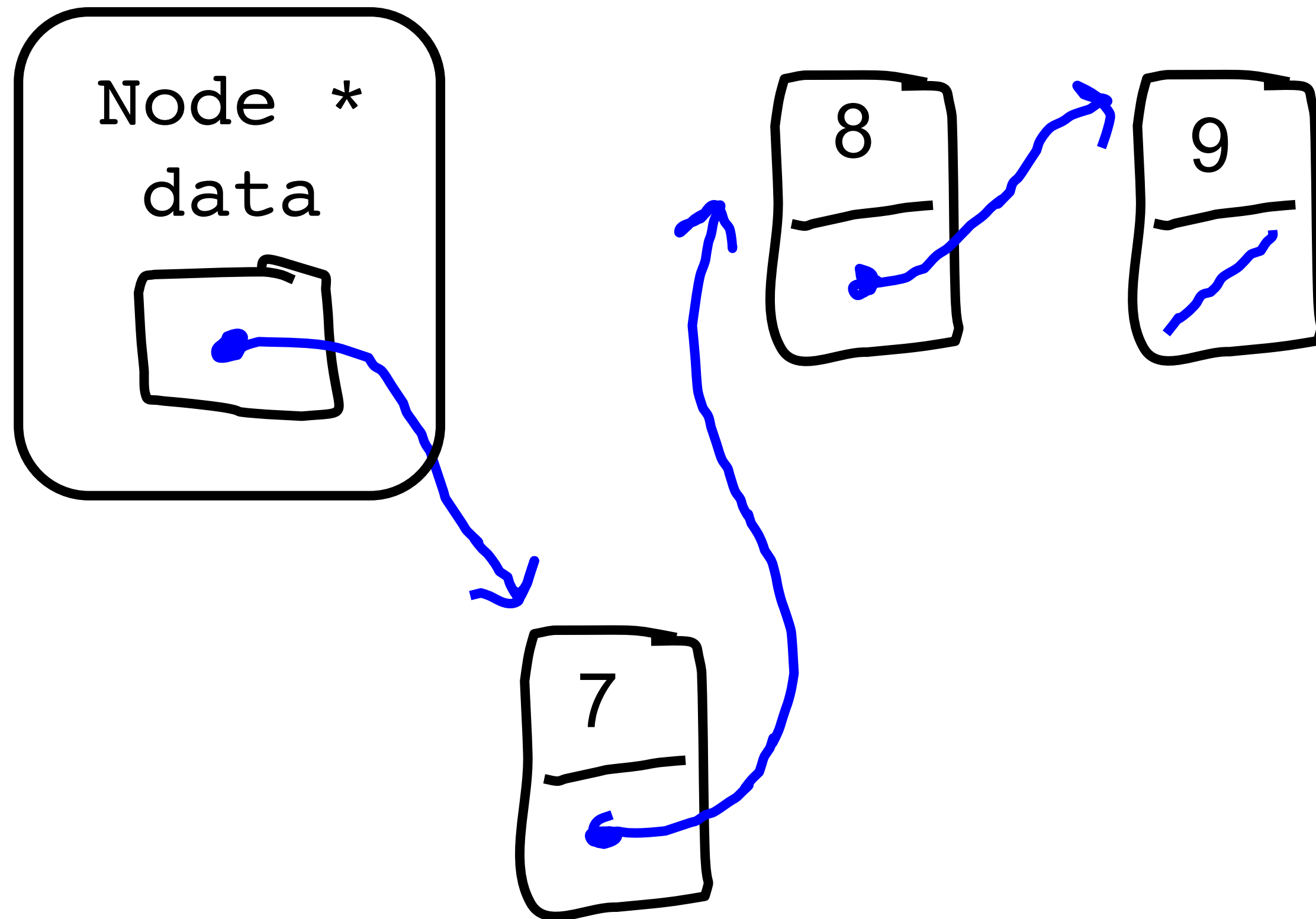
$O(1)$



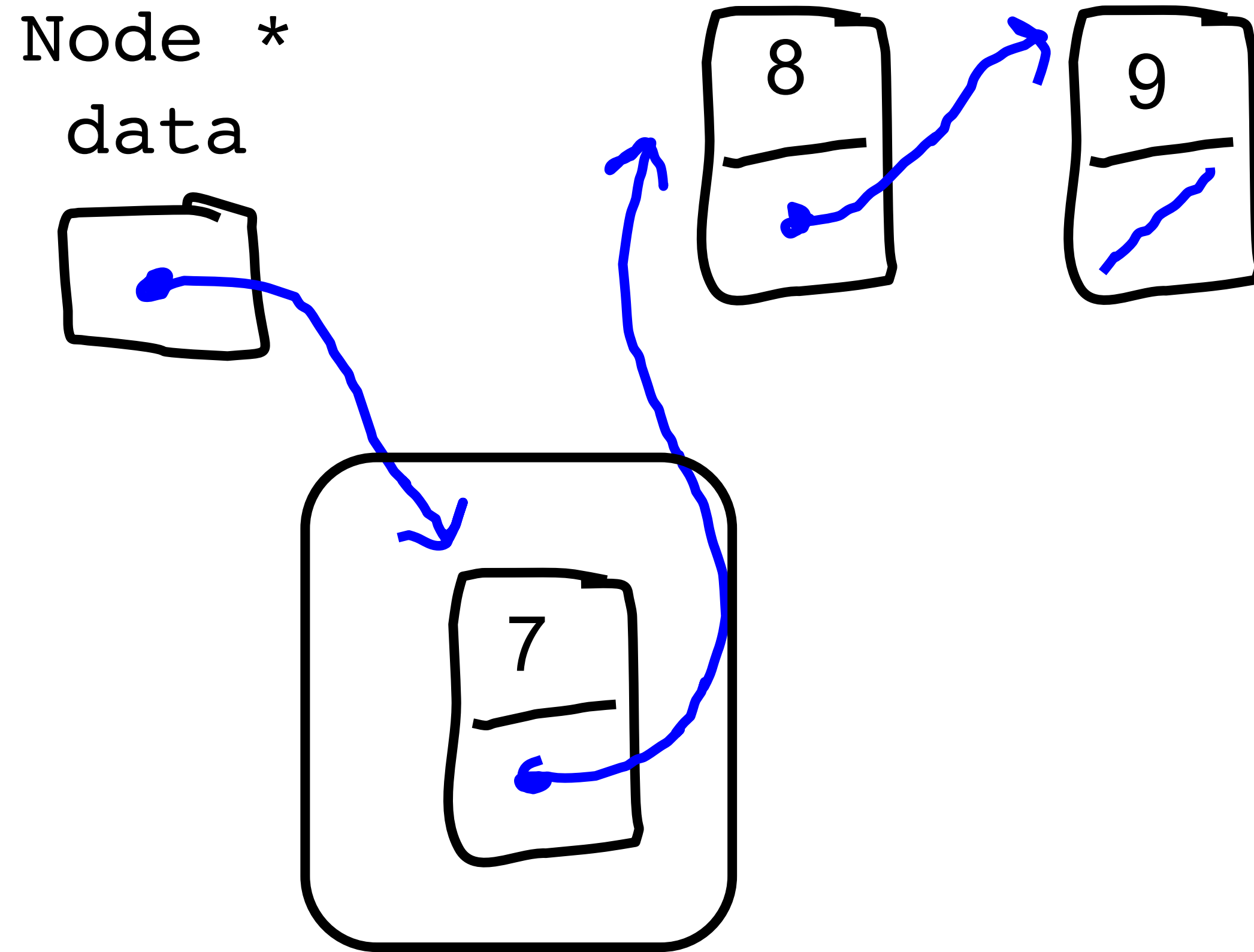
Queue Dequeue?



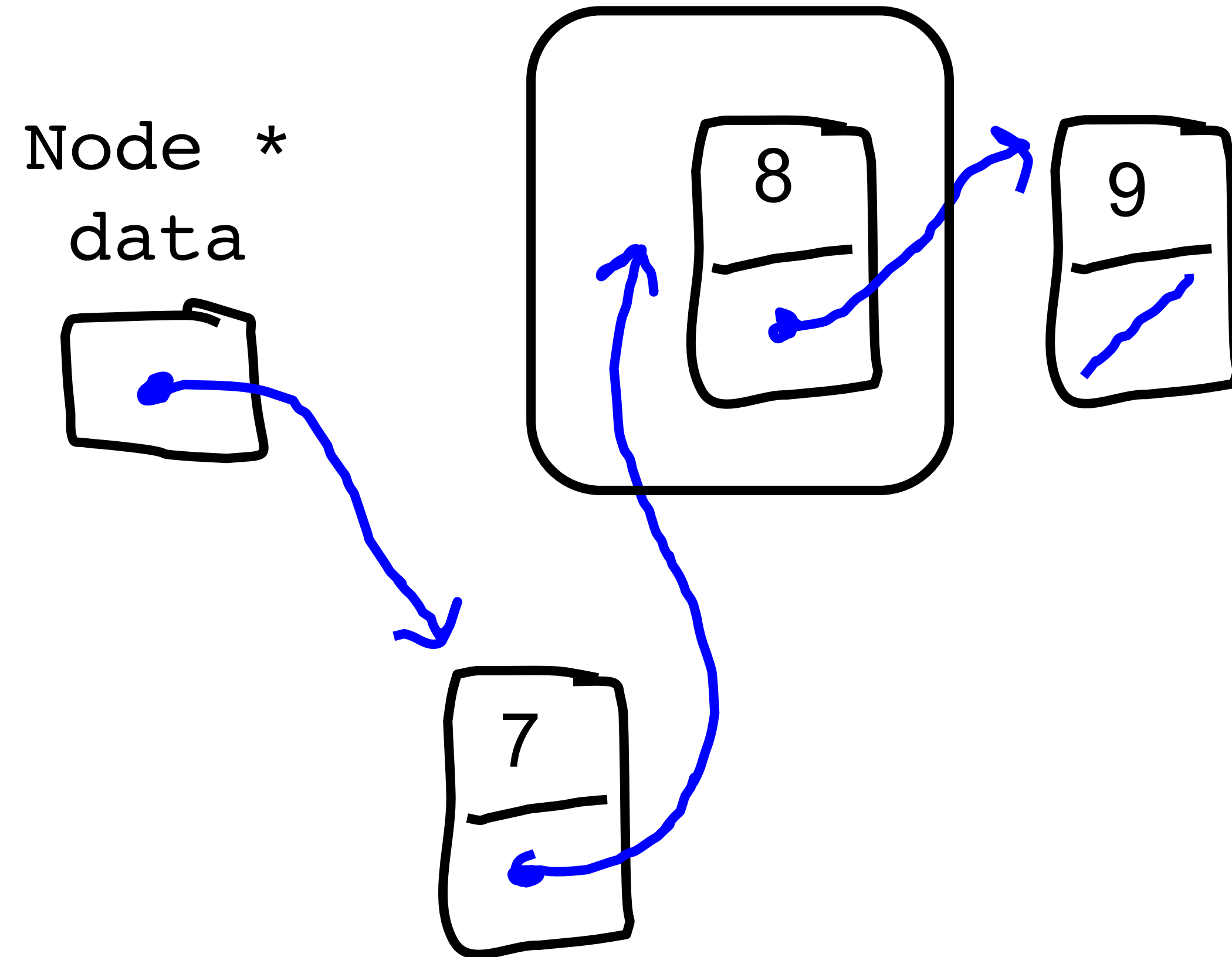
Queue Dequeue?



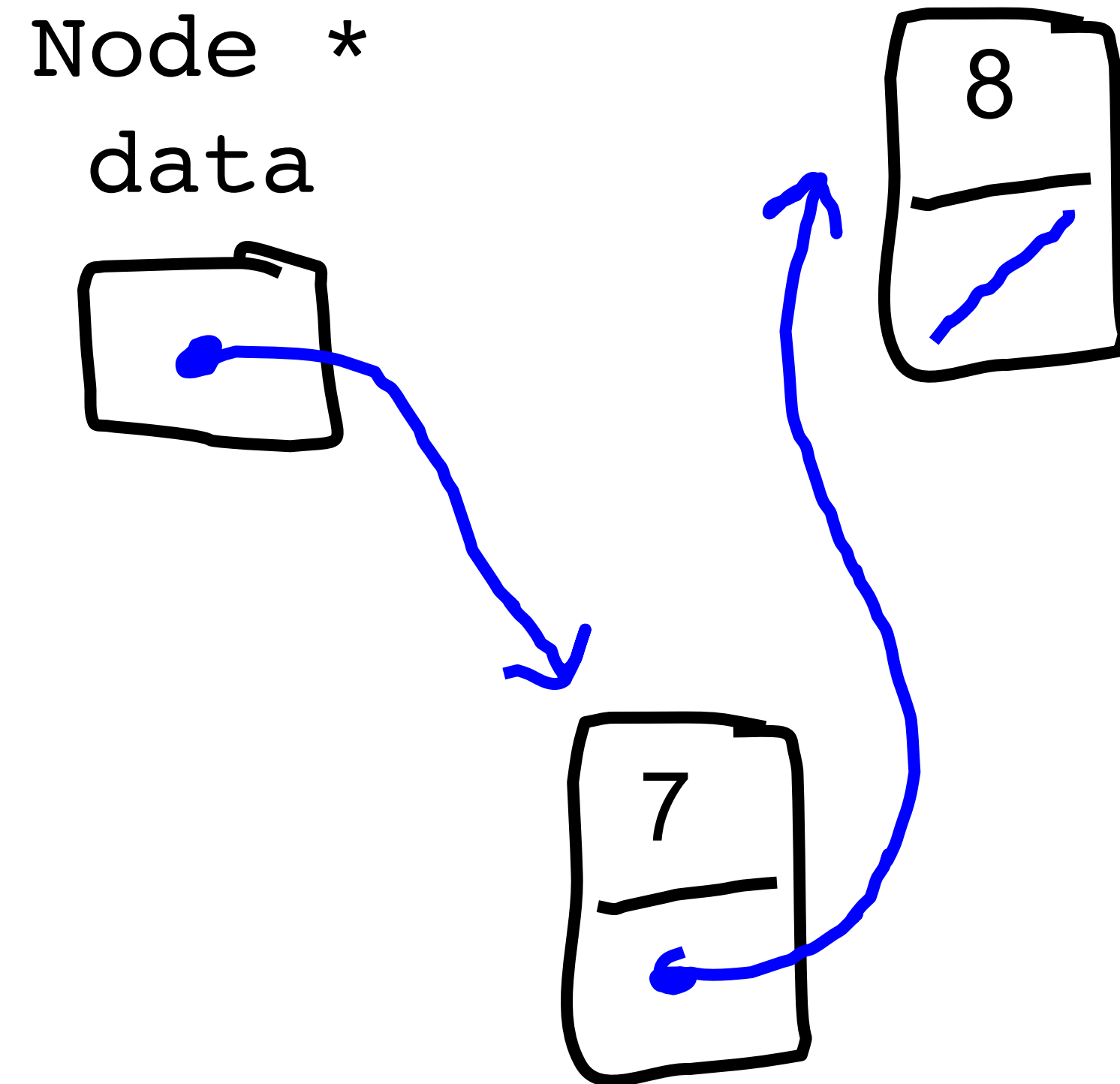
Queue Dequeue?



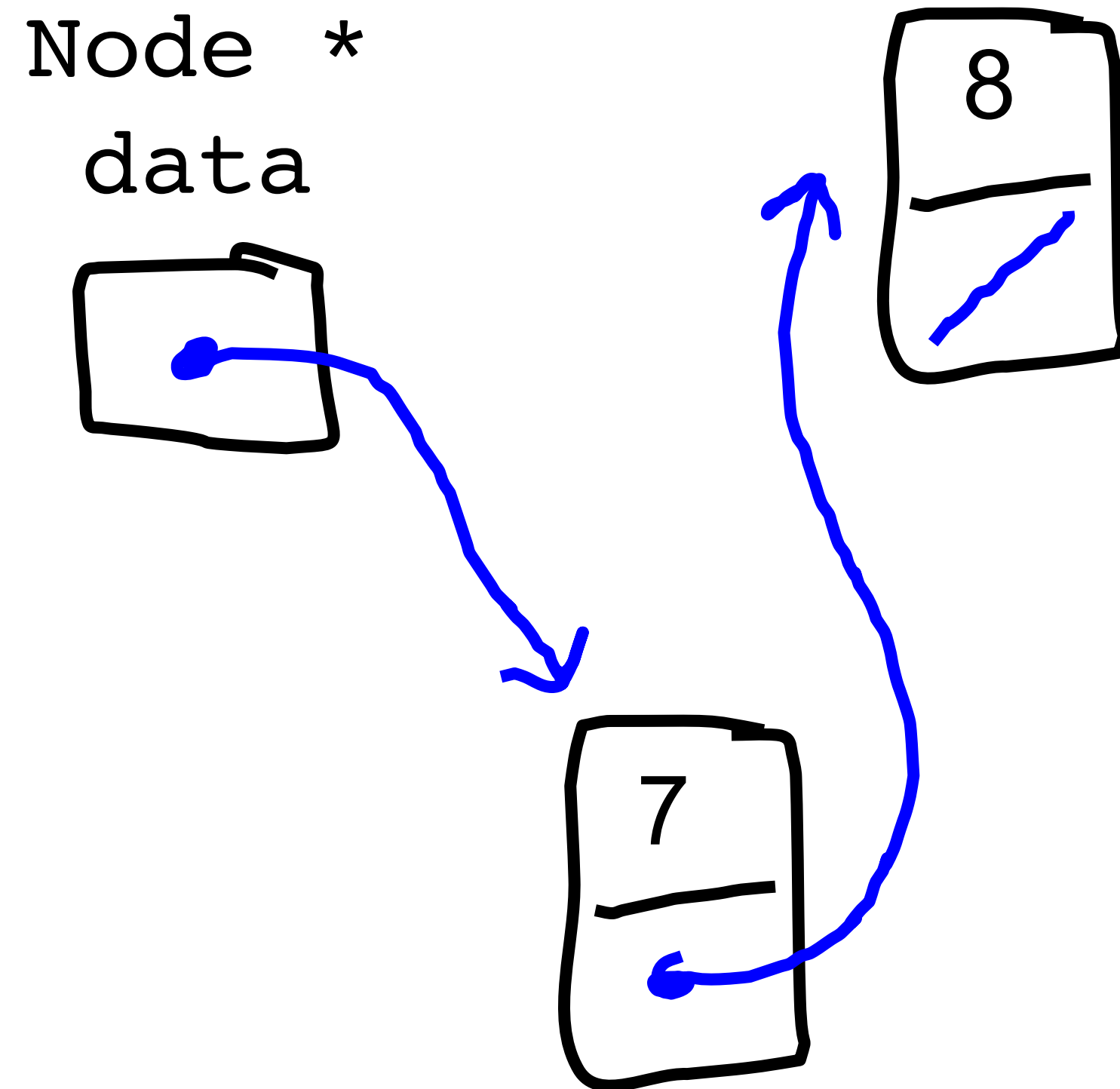
Queue Dequeue?



Queue Dequeue?



Queue Dequeue?

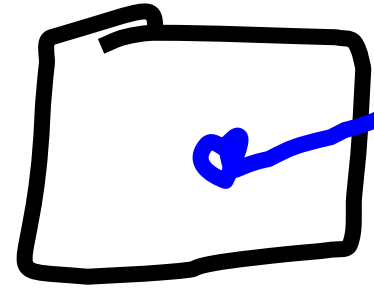


$O(n)$

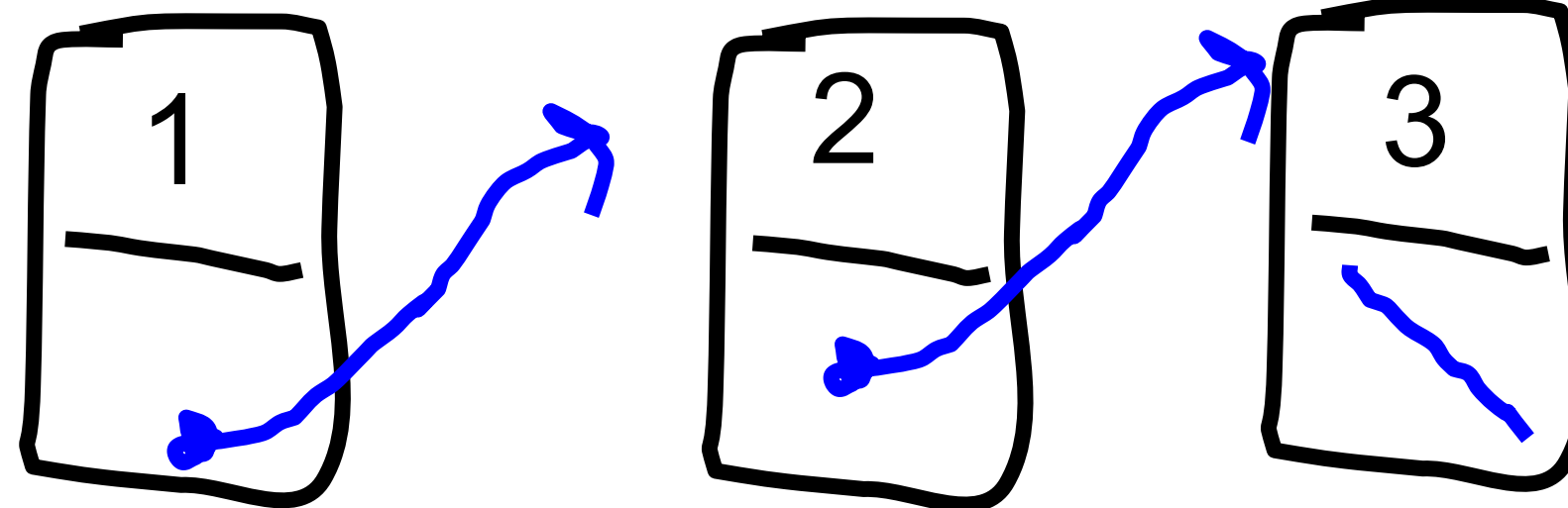
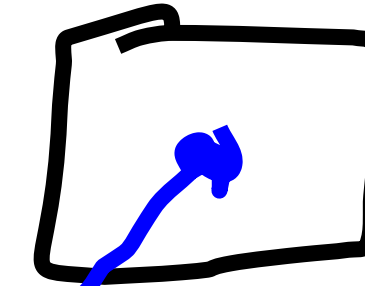
Always a Better Way

Actual Queue: Enqueue

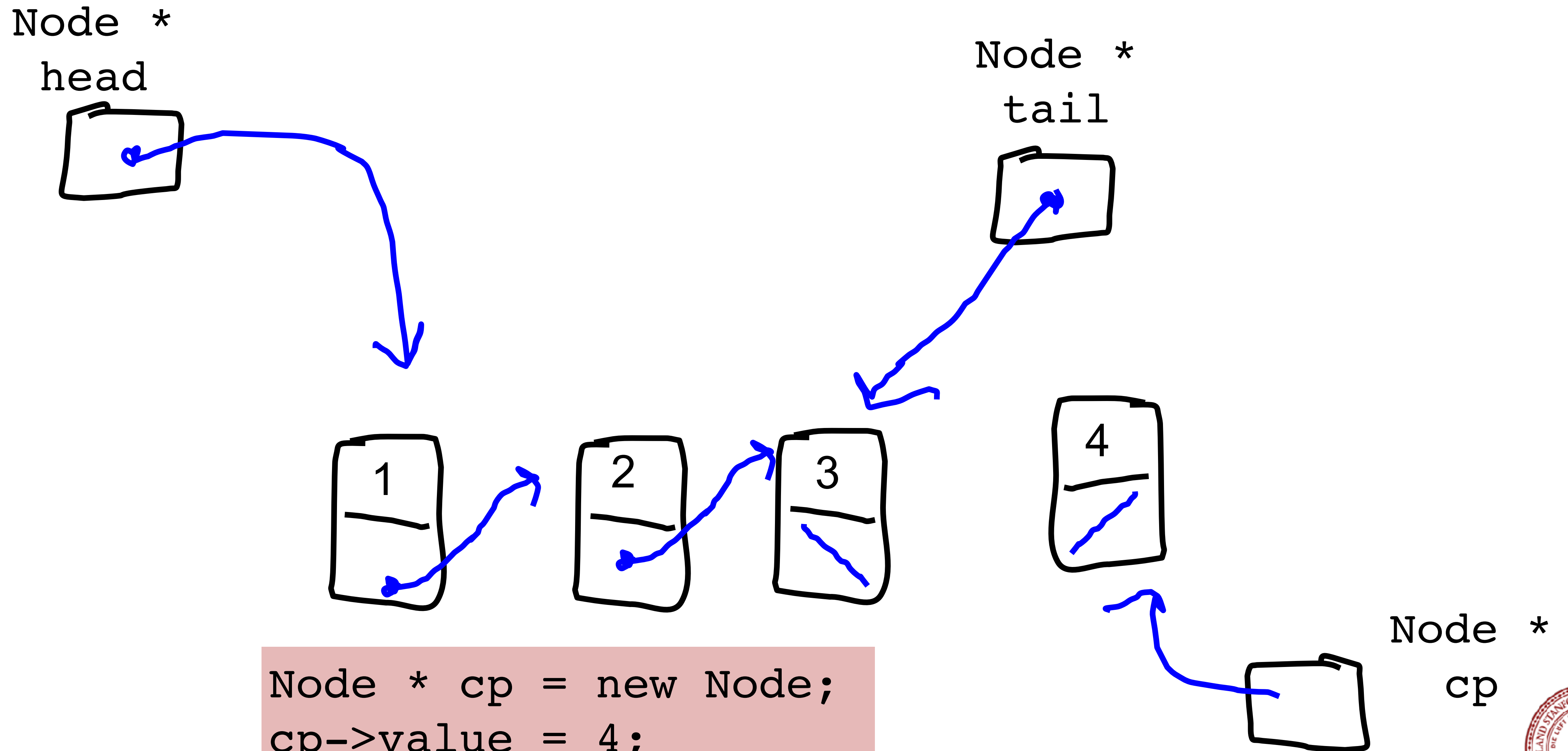
Node *
head



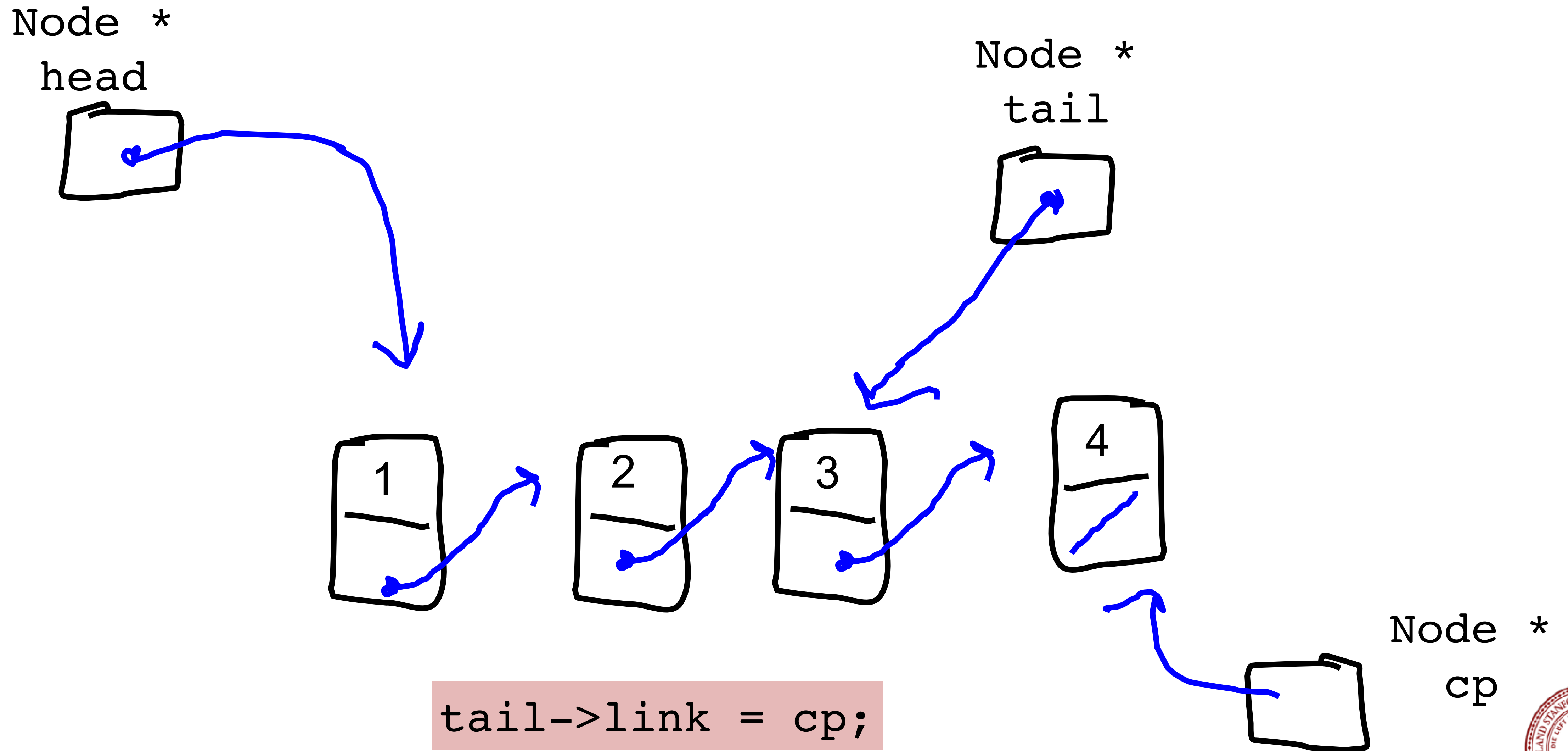
Node *
tail



Actual Queue: Enqueue

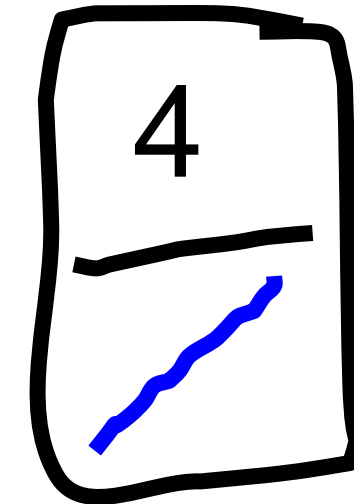
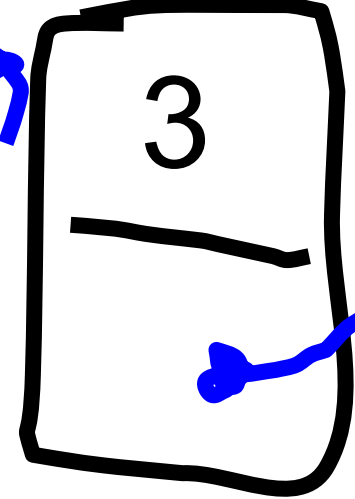
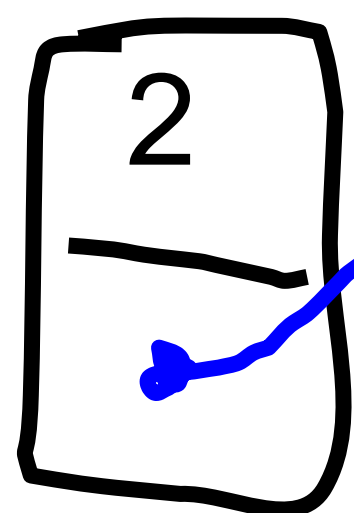
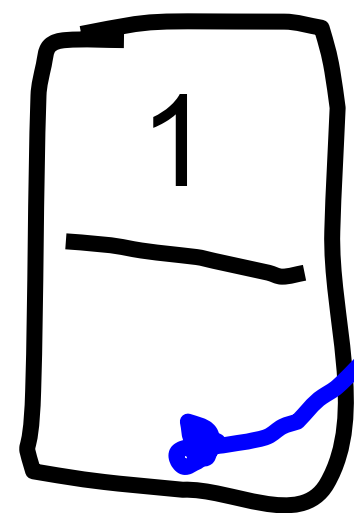
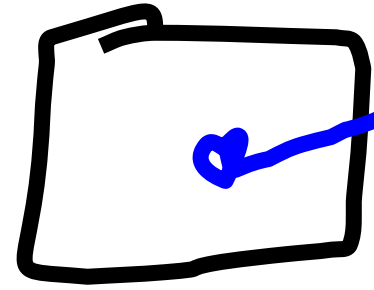


Actual Queue: Enqueue

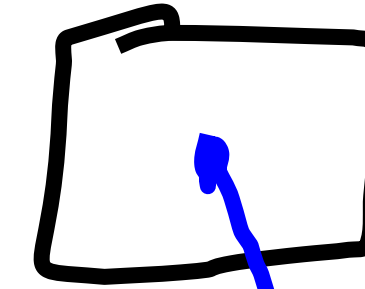


Actual Queue: Enqueue

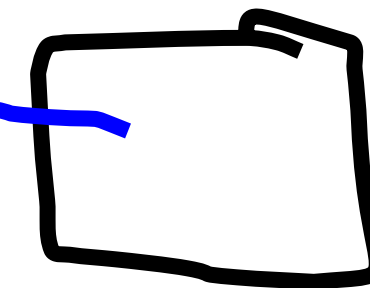
Node *
head



Node *
tail



Node *
cp

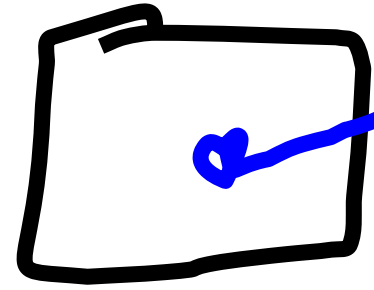


```
tail = cp;
```

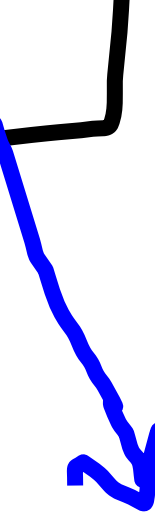
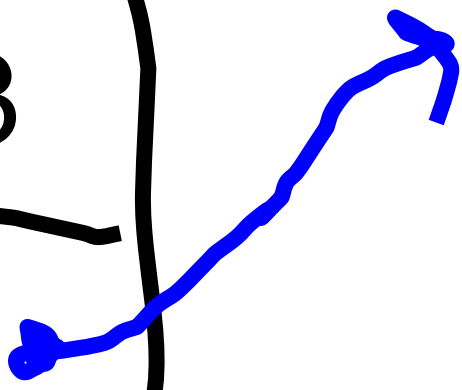
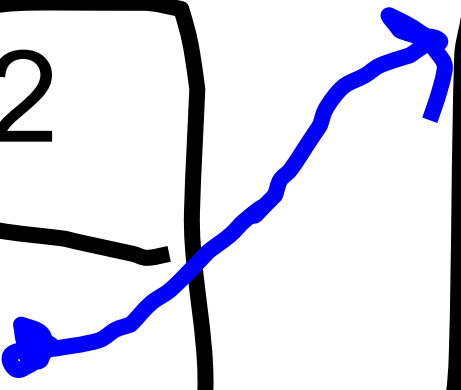
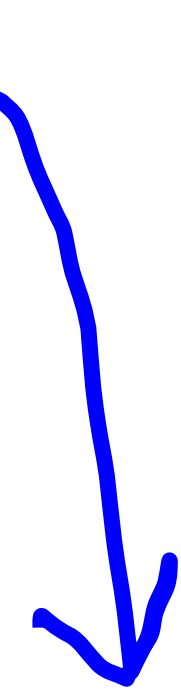
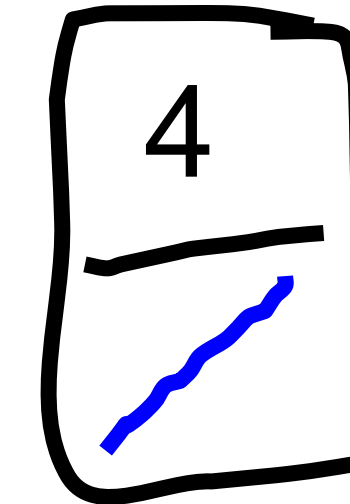
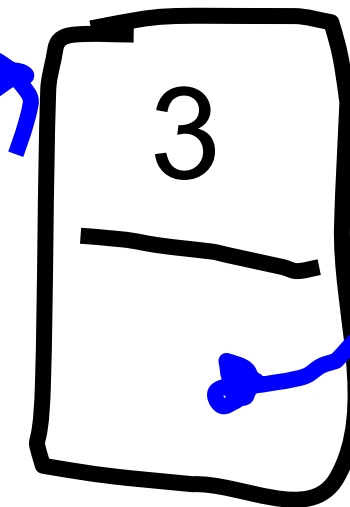
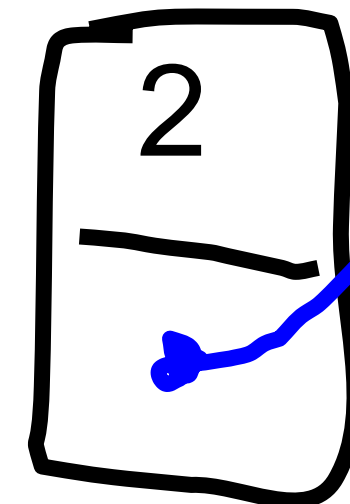
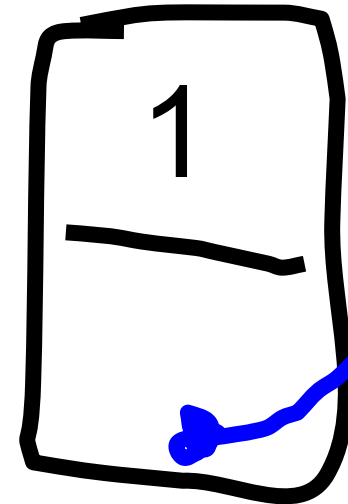
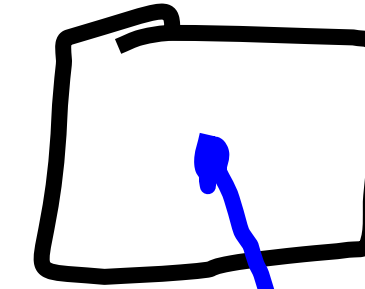


Actual Queue: Enqueue

Node *
head



Node *
tail

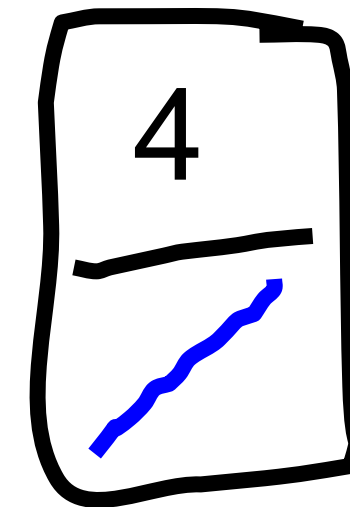
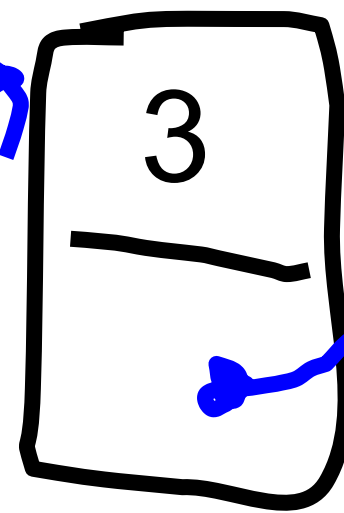
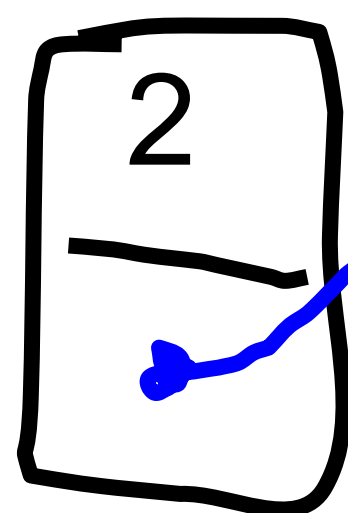
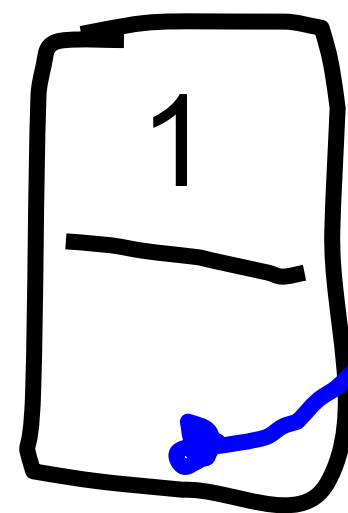
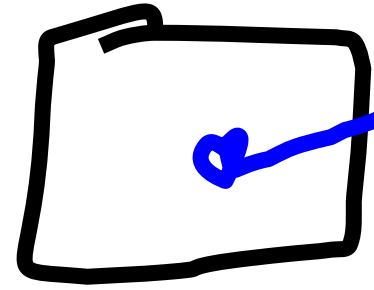


```
return;
```

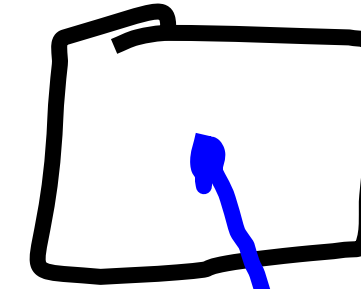


Actual Queue: Enqueue

Node *
head



Node *
tail



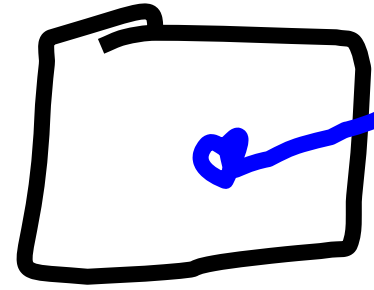
$O(1)$



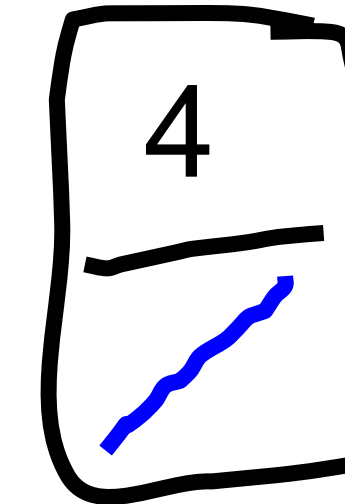
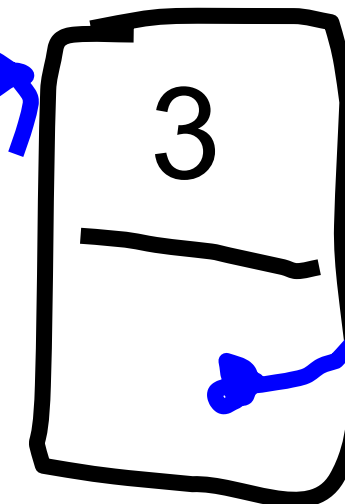
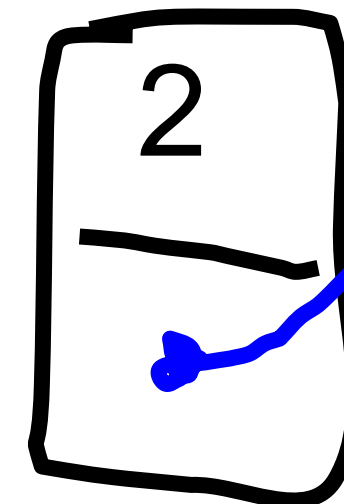
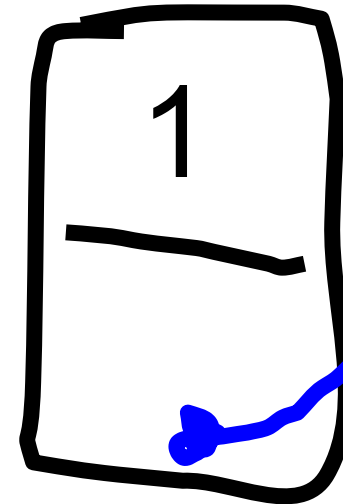
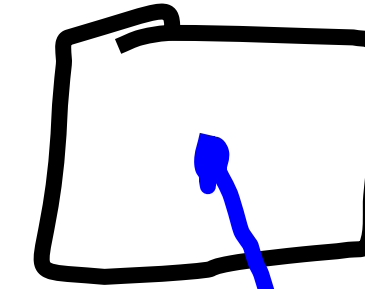
Dequeue

Actual Queue: Dequeue

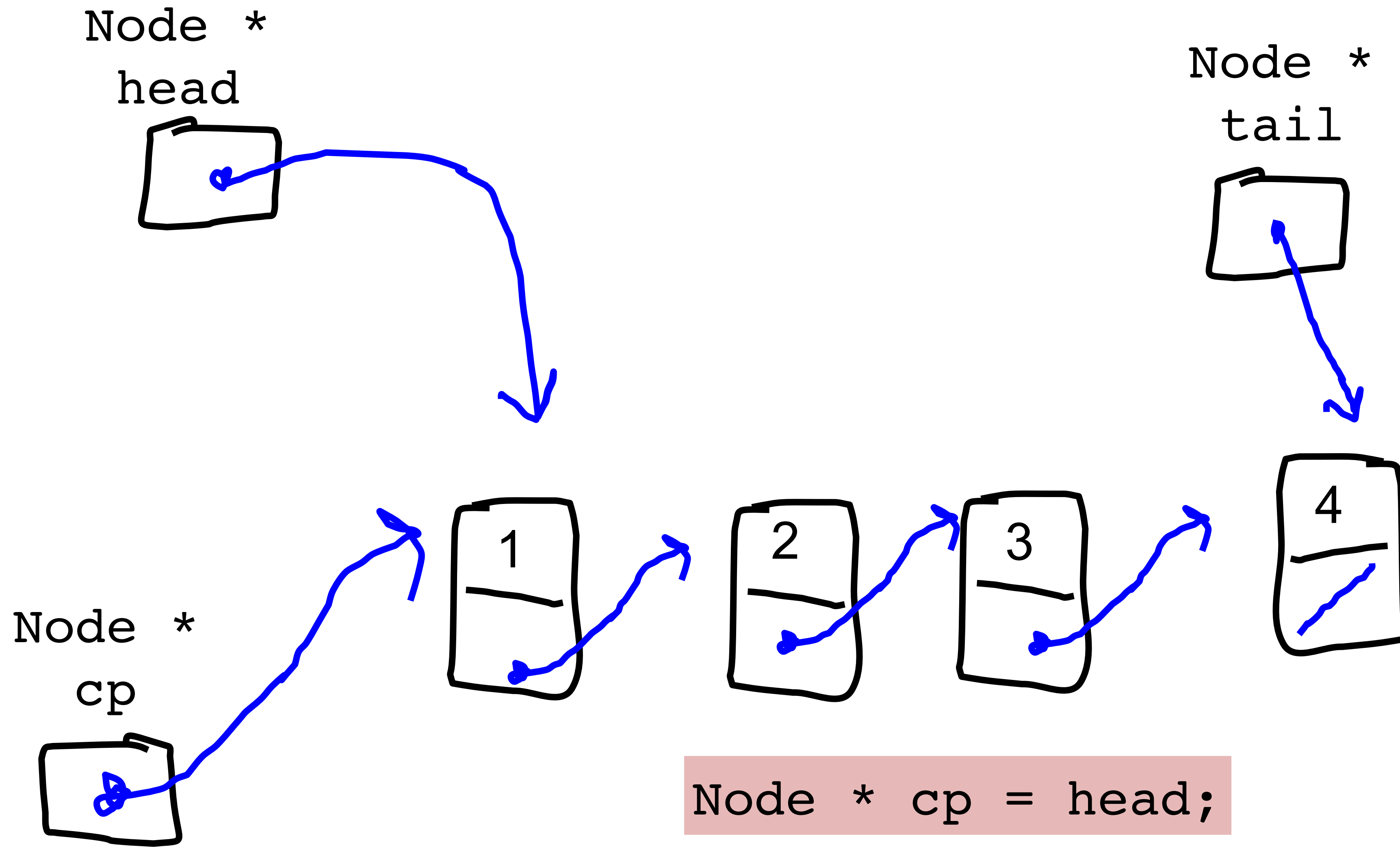
Node *
head



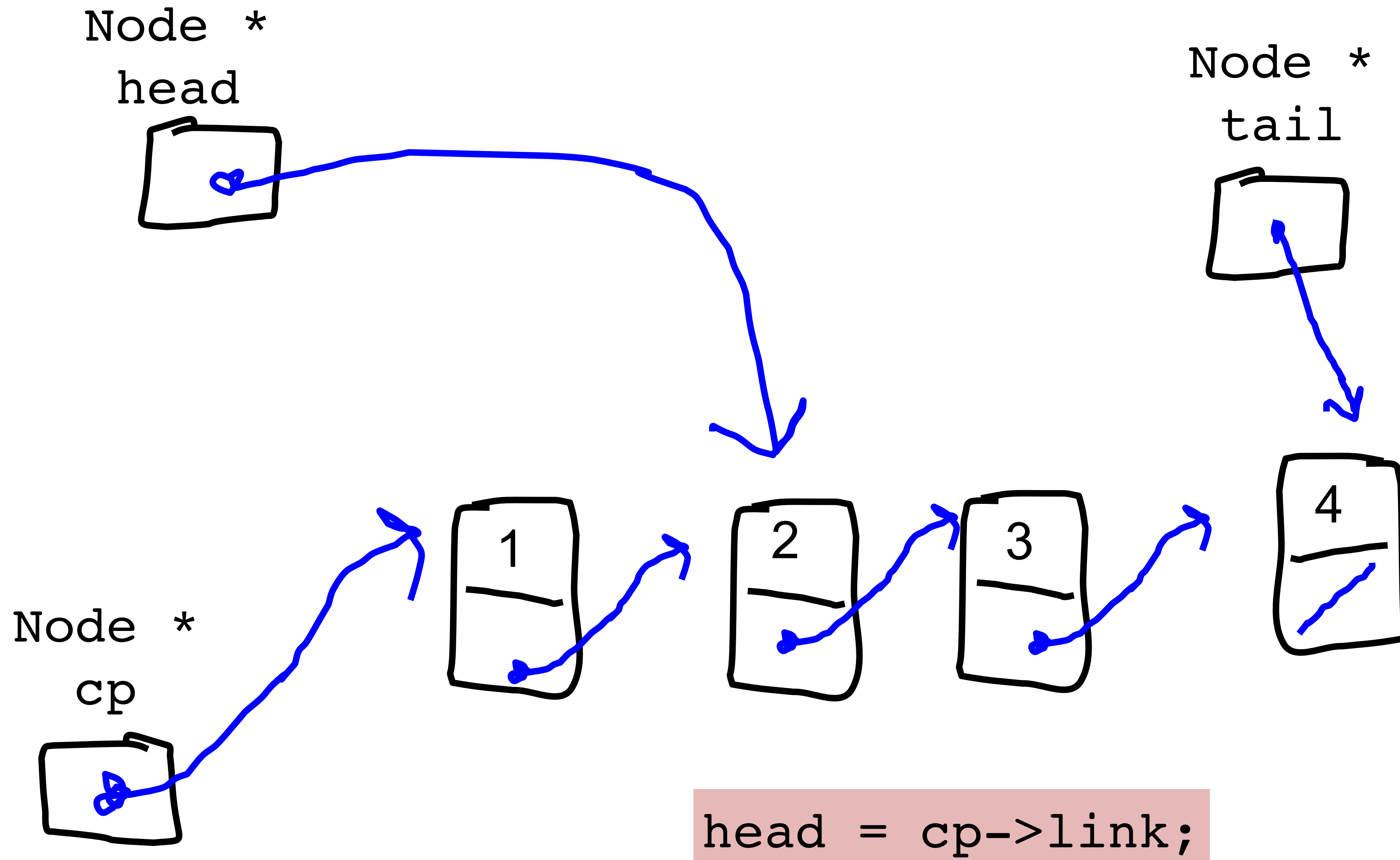
Node *
tail



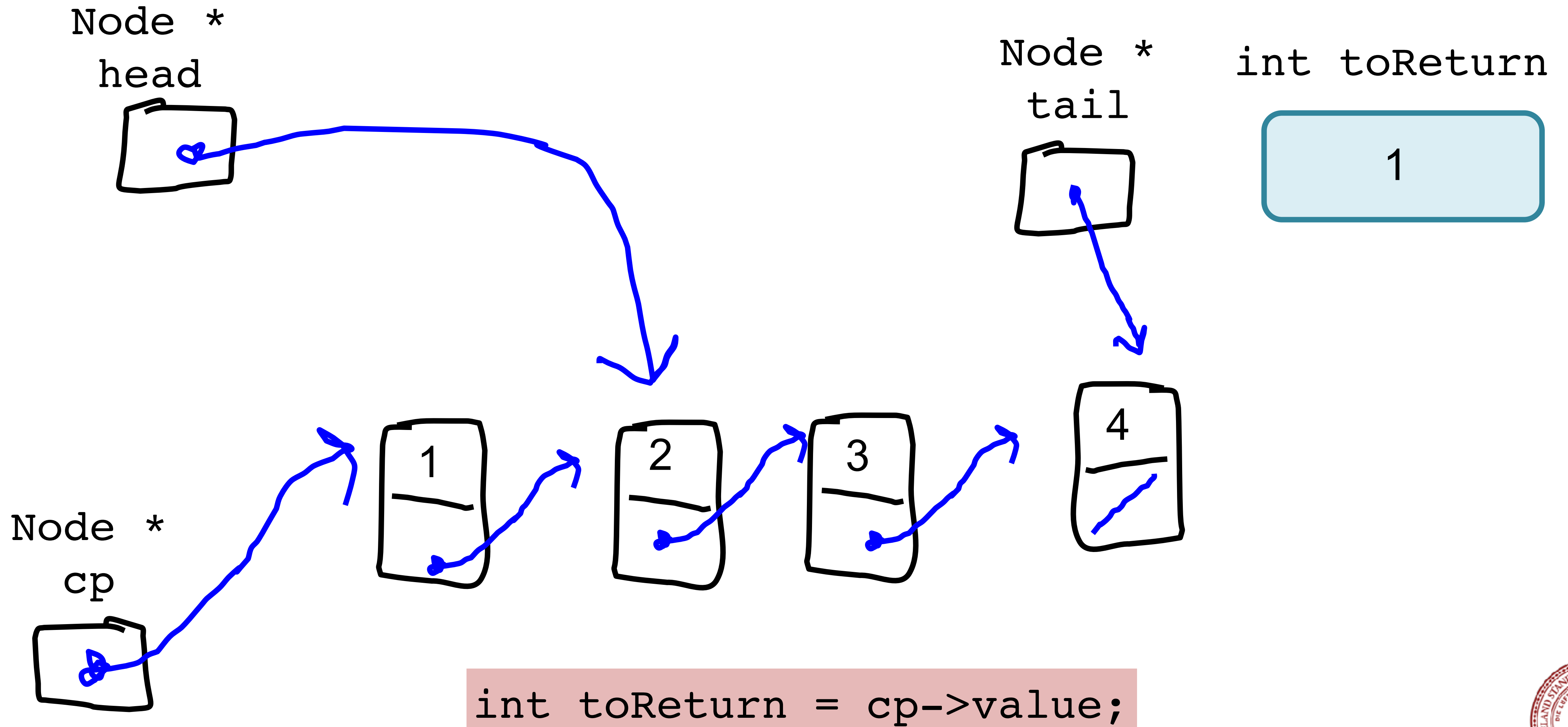
Actual Queue: Dequeue



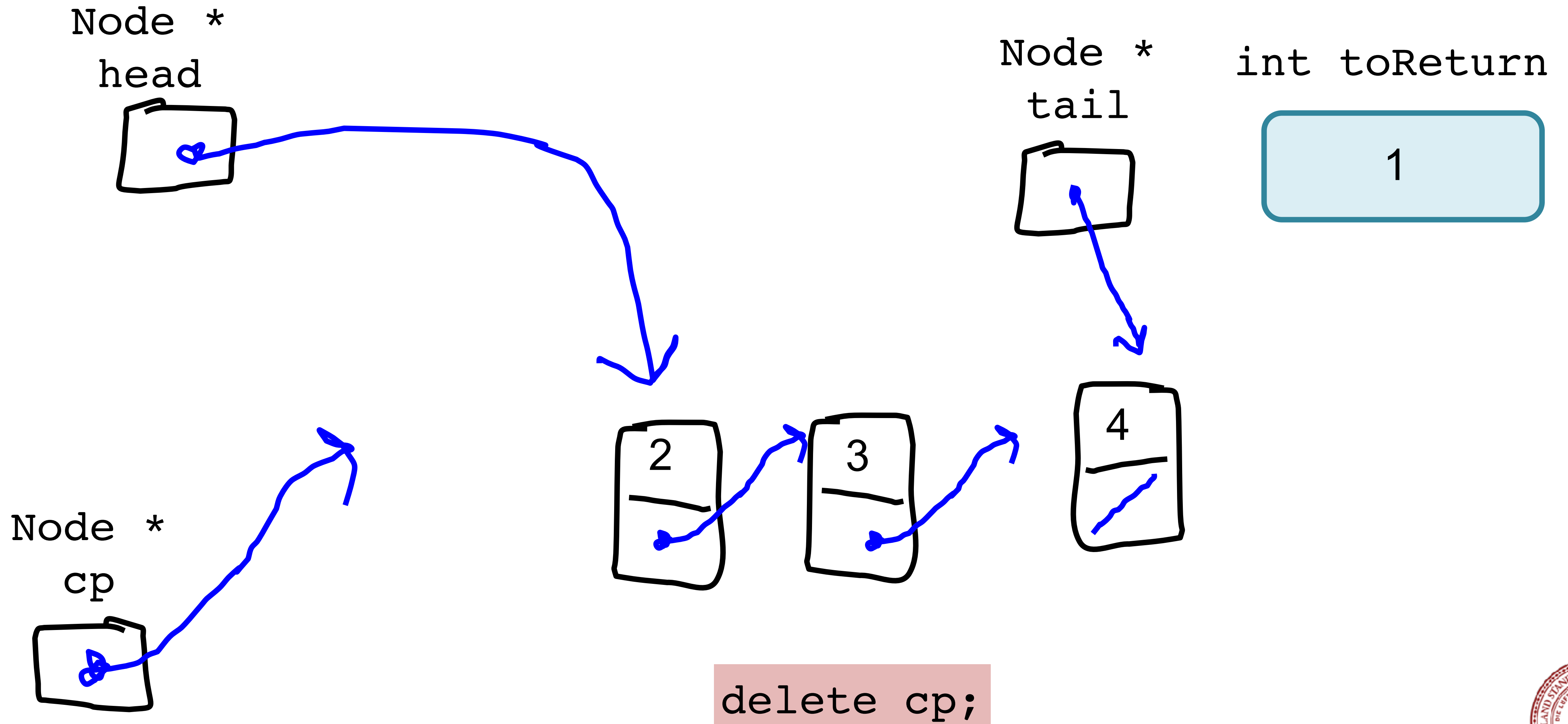
Actual Queue: Dequeue



Actual Queue: Dequeue

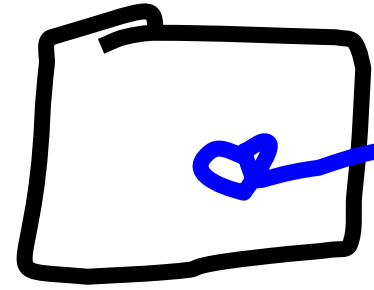


Actual Queue: Dequeue

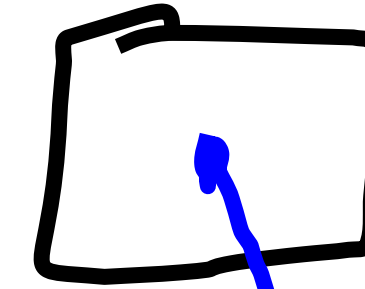


Actual Queue: Dequeue

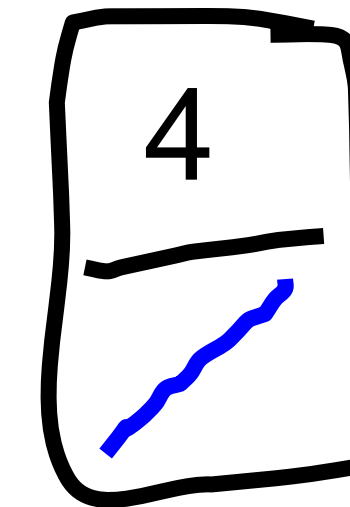
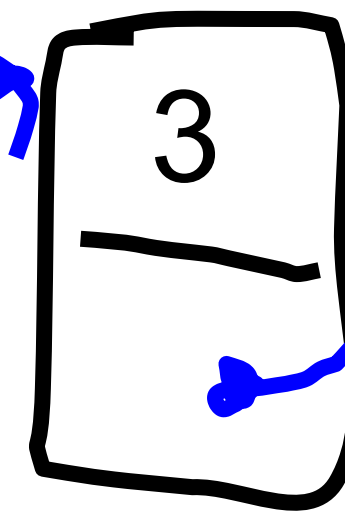
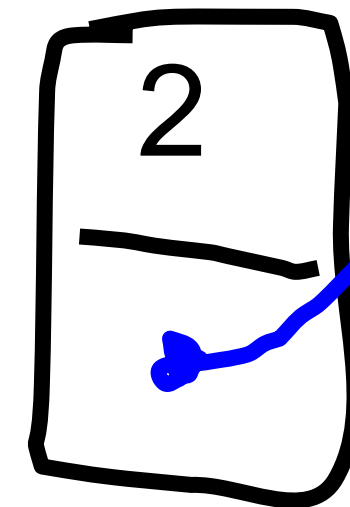
Node *
head



Node *
tail



int toReturn

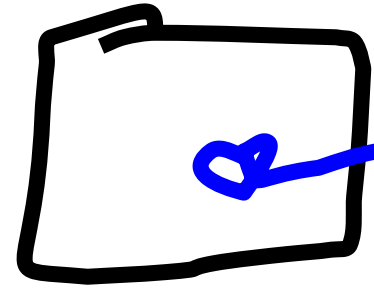


```
return toReturn;
```

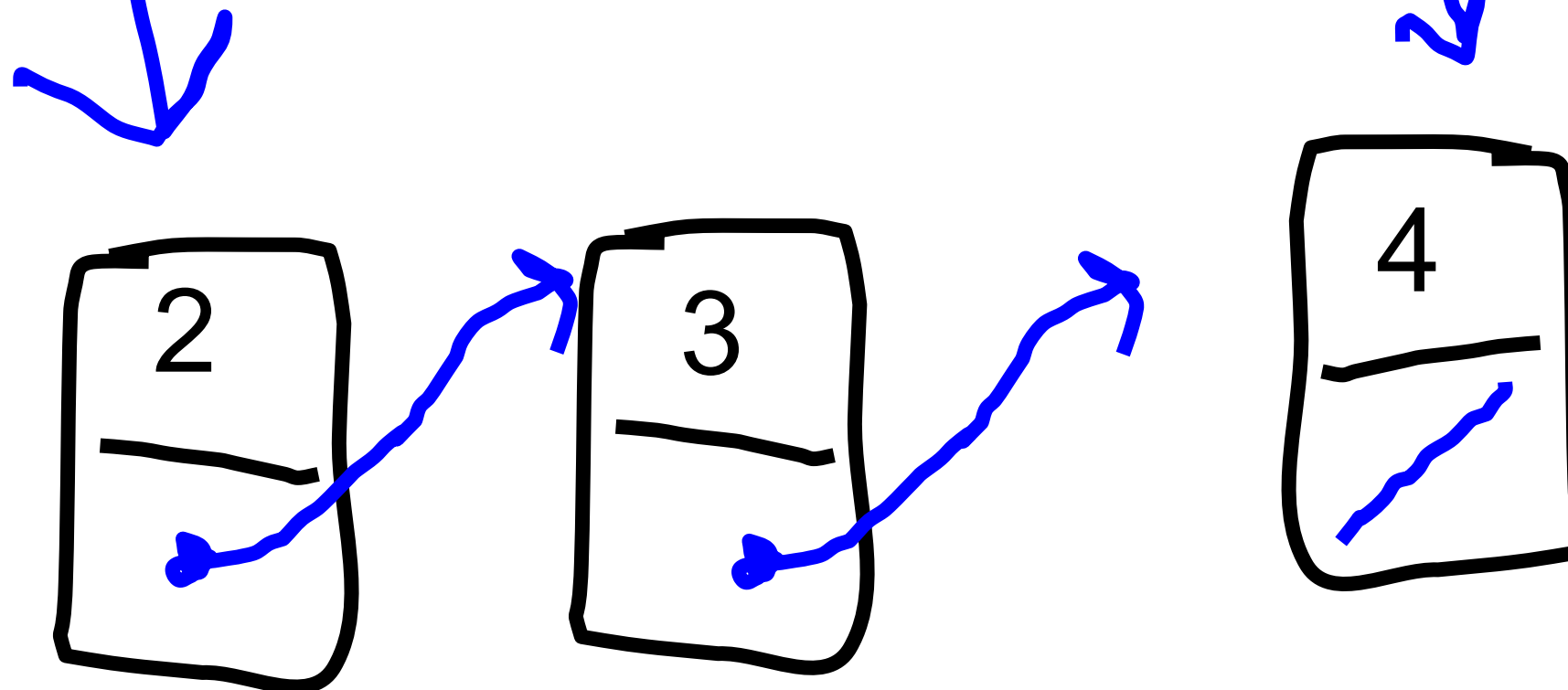
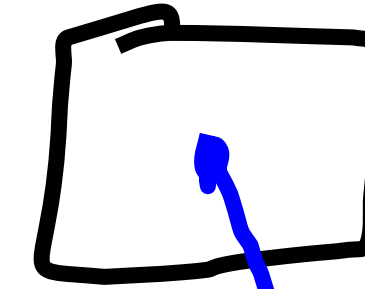


Actual Queue: Dequeue

Node *
head



Node *
tail



$O(1)$



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

$\mathcal{O}(1)$

