

CSCI 132:

Basic Data Structures and Algorithms

Sorting (Quick Sort)

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Spring 2025

Quick Sort is a sorting algorithm that works by partitioning an array around a certain element in the array, called a pivot. This is a recursive method that then sorts the sections of the array to the left of the pivot, and to the right of the pivot.

Quick sort is a **Divide and Conquer** algorithm, which involves dividing the problem into smaller sub-problems (divide), recursively solving the smaller problems (conquer), and combining the sub problems to get the final solution for the original problem

Quick sort is rather complex. I don't expect you to memorize the code, and if you don't fully understand the code, *that is fine!*

You should, however, be able to describe how quick sort works from a high level, and be able to draw out the steps if given an example array

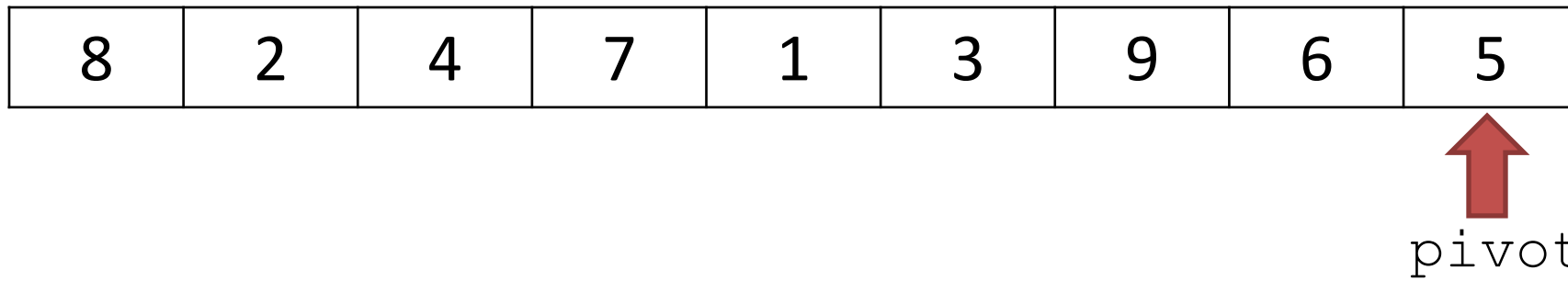
You should also know the time complexity of the sorting algorithms that we talk about



8	2	4	7	1	3	9	6	5
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The first step of Quick Sort is to select a pivot, and to get the pivot sorted to its correct position

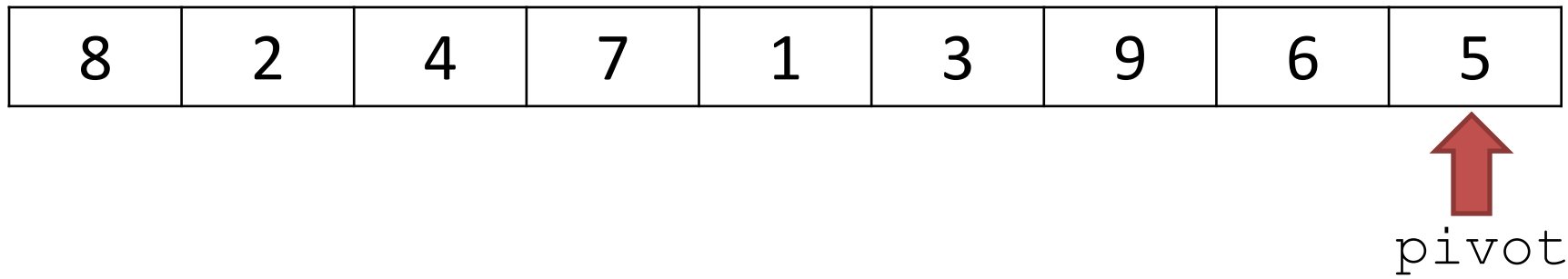
→ This step is known as **partitioning**



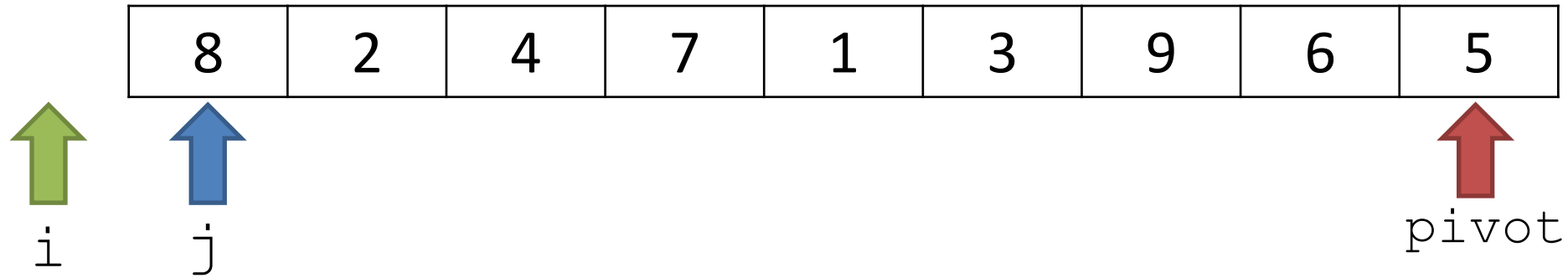
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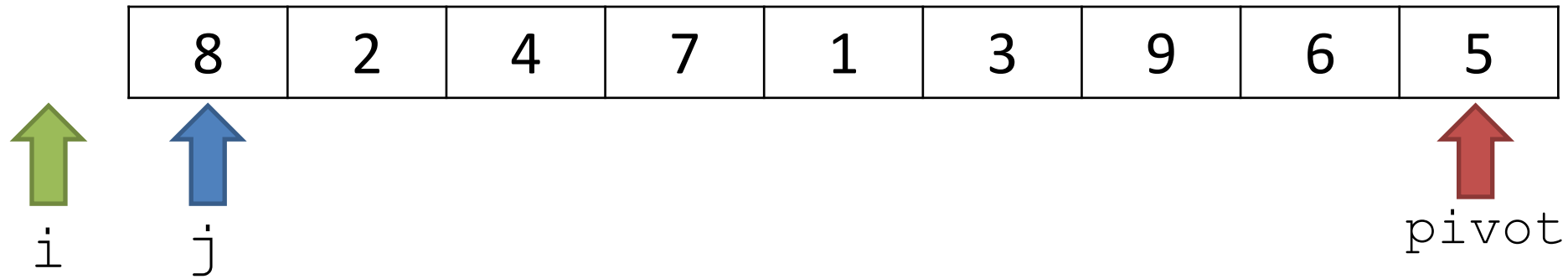
There are many ways to select a pivot, but to keep things simple, the last element of the array will be the pivot



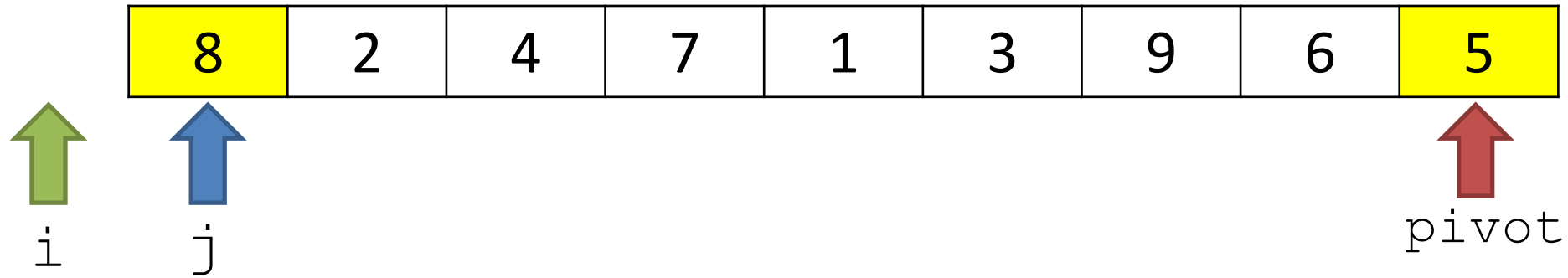
We are going to define two pointers i and j , that will help us get the pivot sorted correctly



j will be defined to be the starting point of the array (0),
and i will be defined to be $(j - 1)$

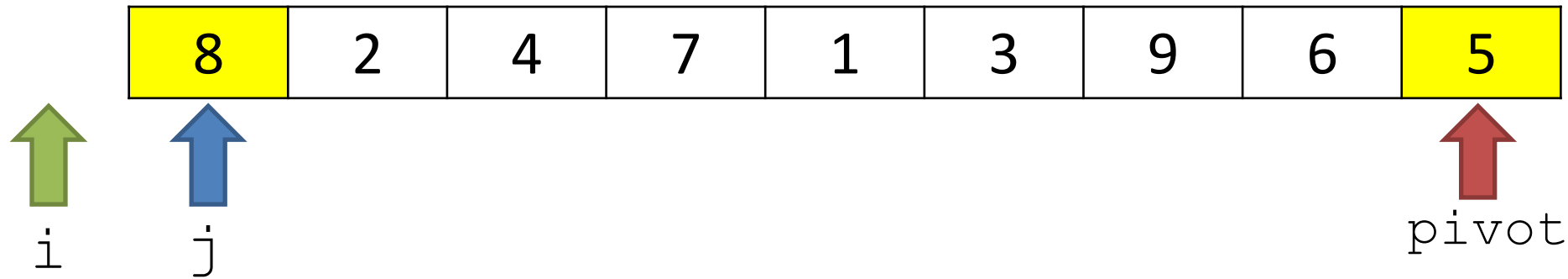


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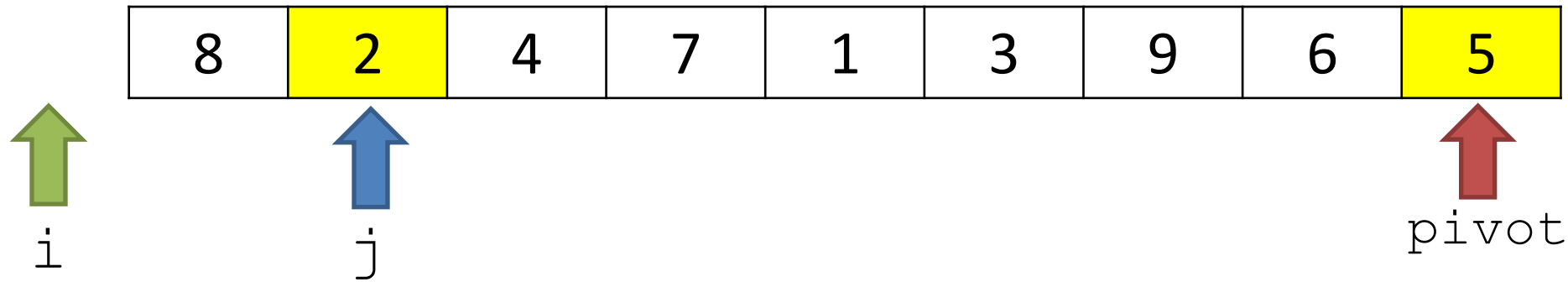


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If not, increase j by 1

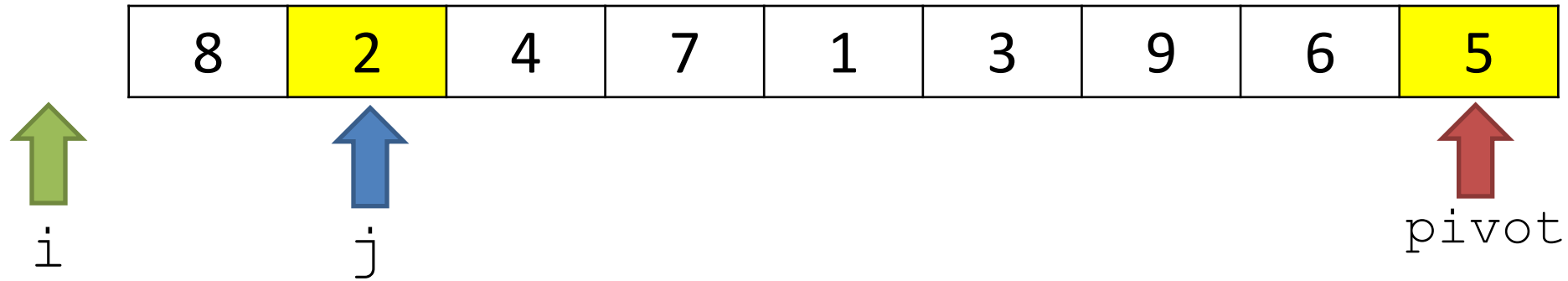


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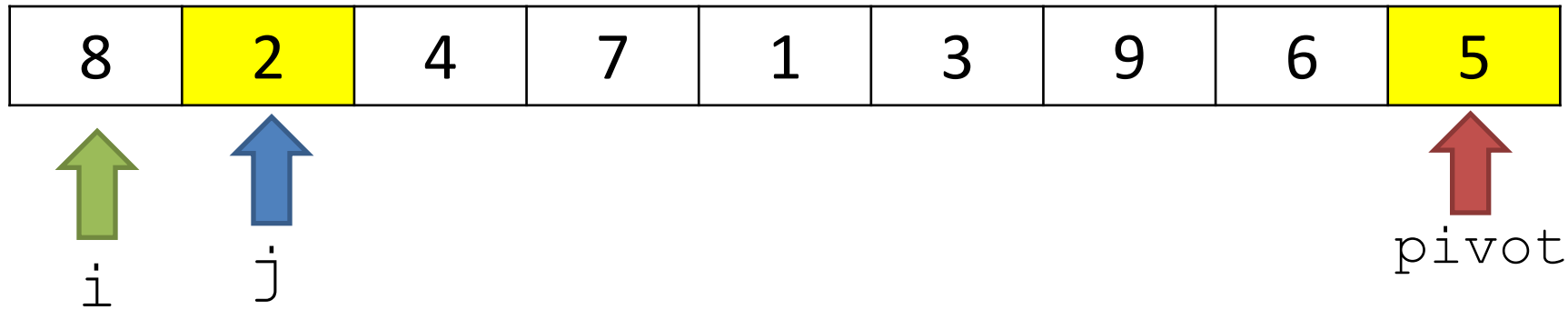
2 is less than 5, so we increase i and then swap!

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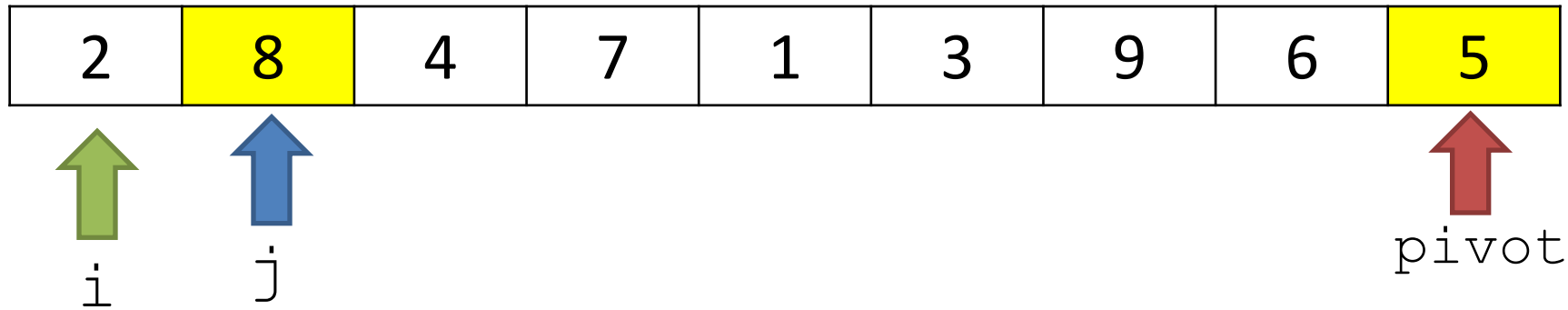
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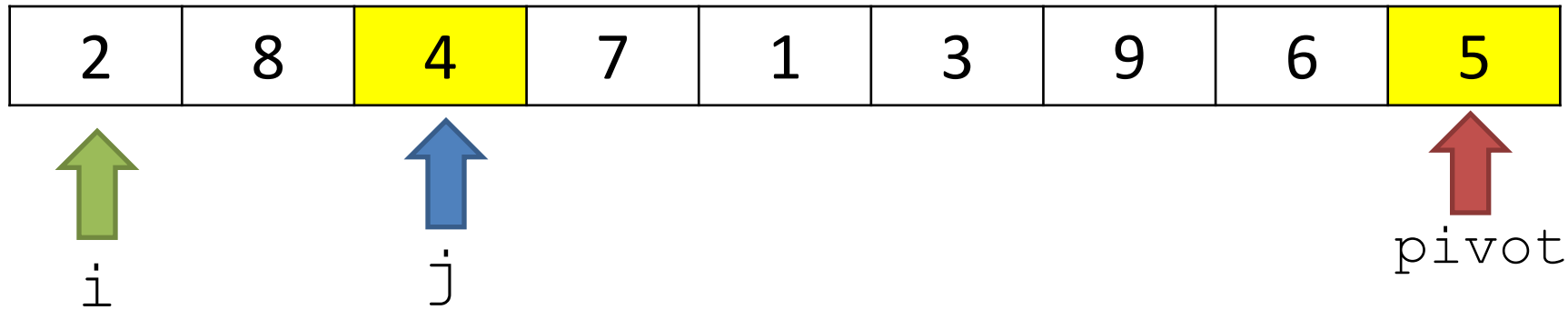
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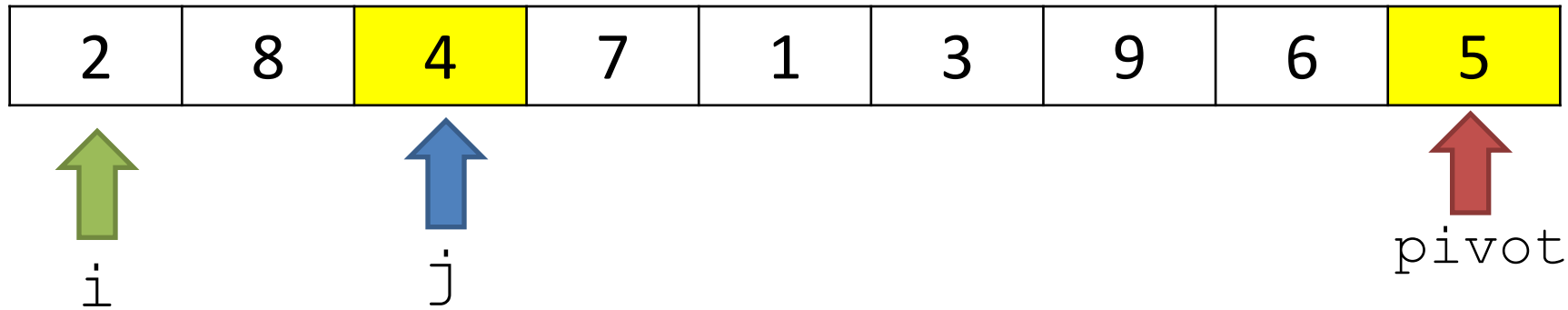


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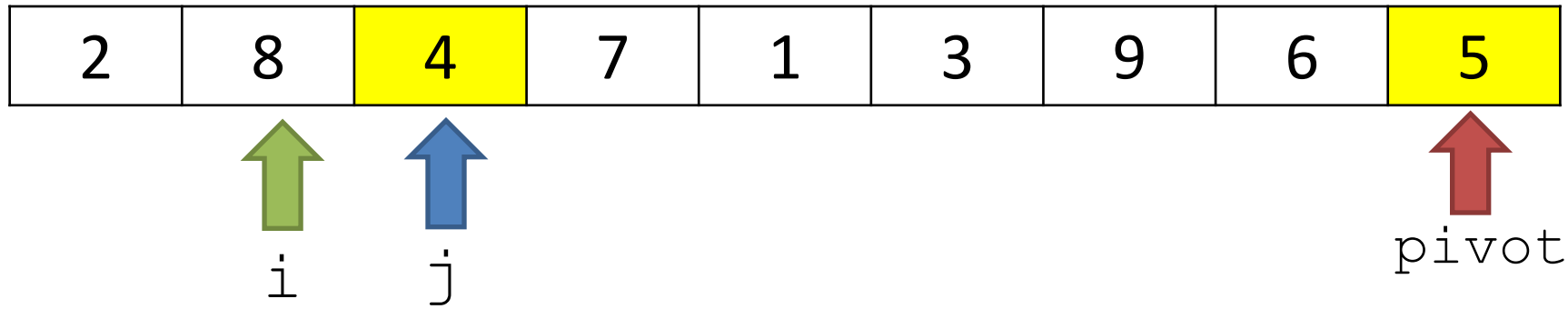
4 is less than 5, so we increase i and then swap!

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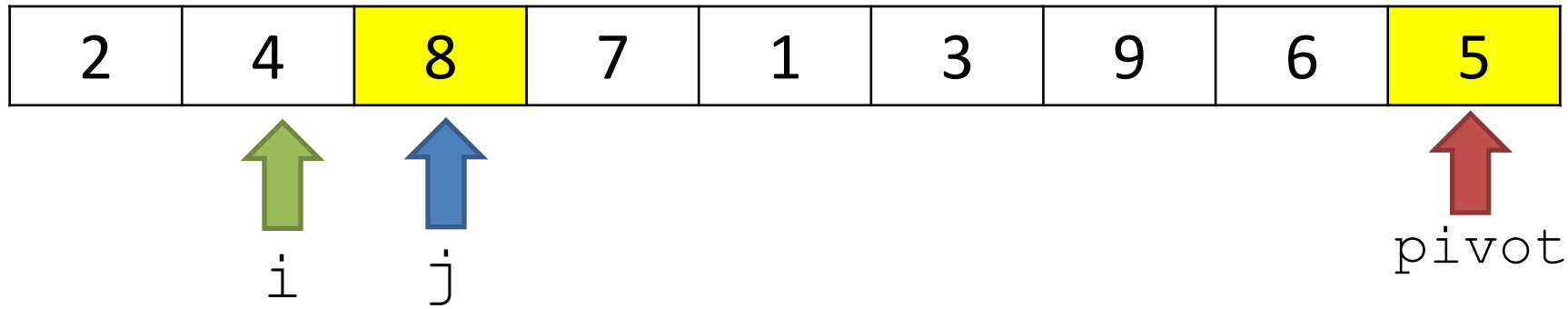
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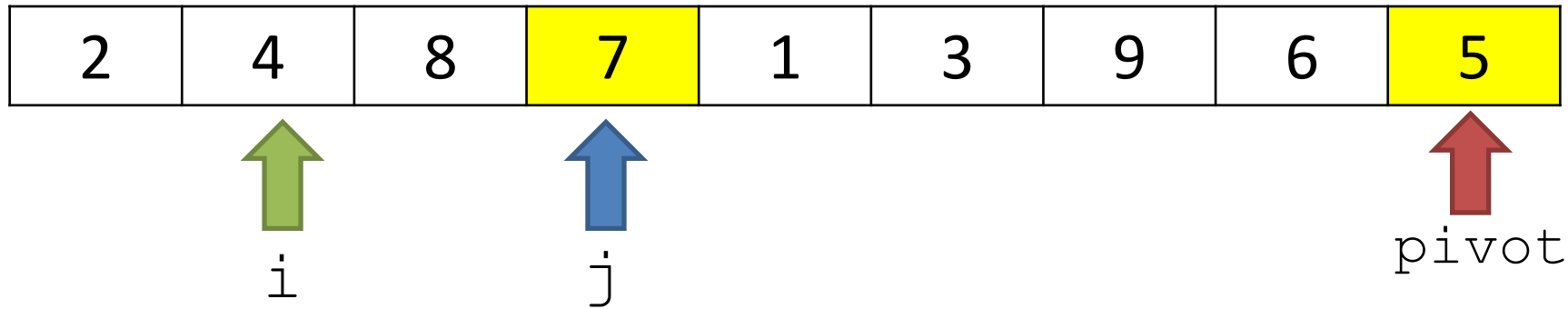
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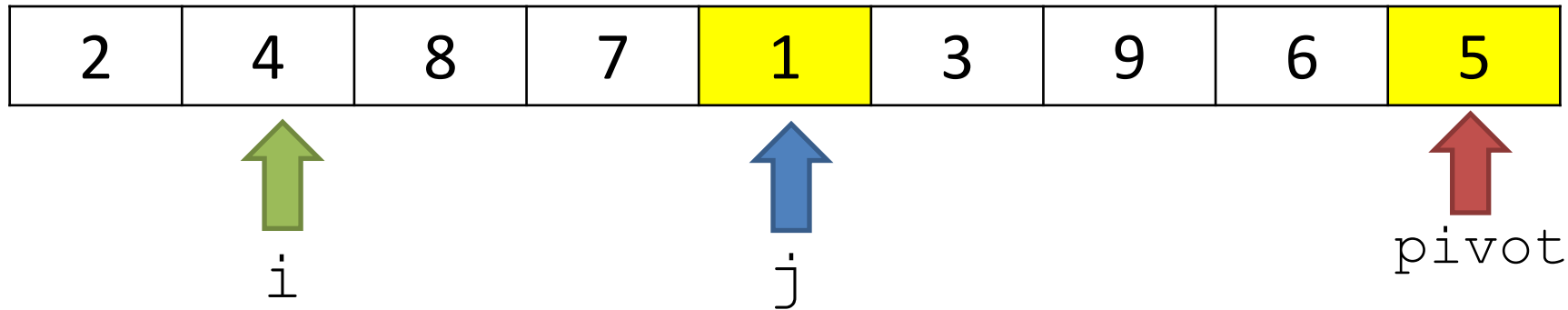


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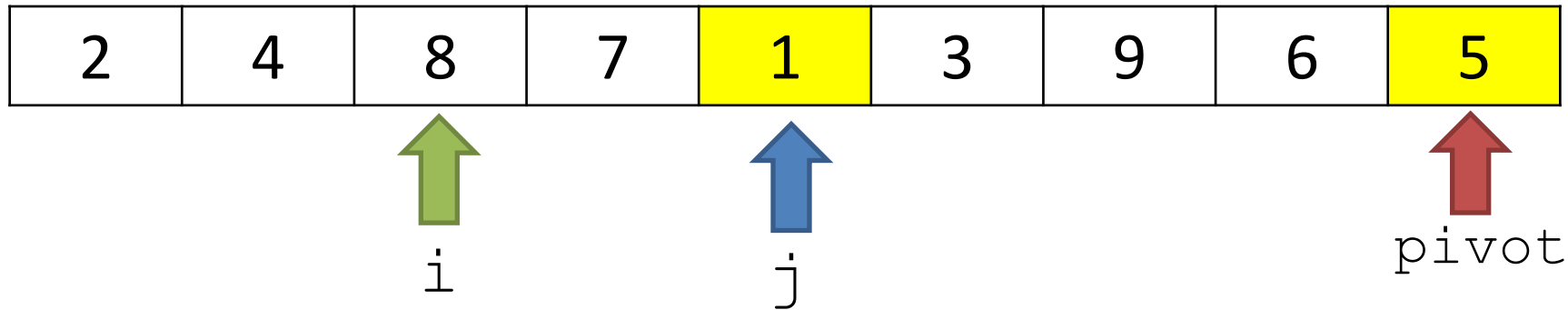


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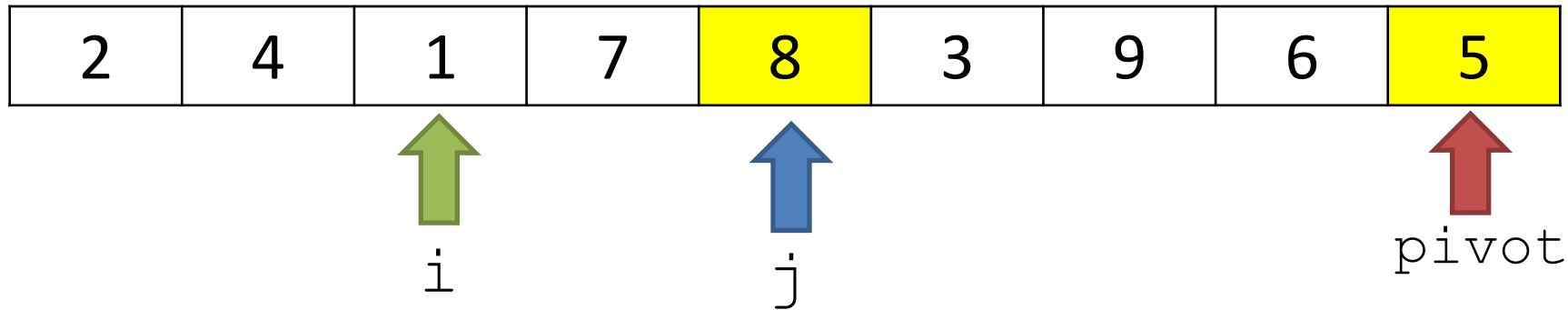


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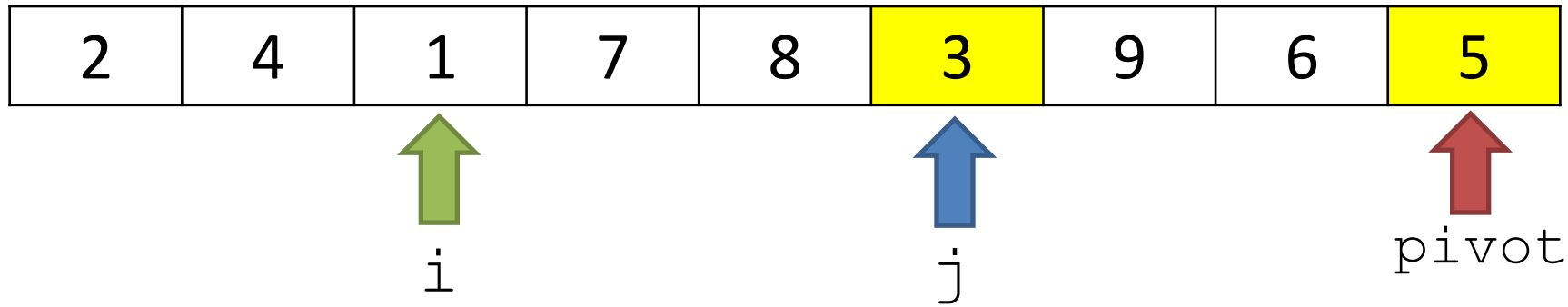


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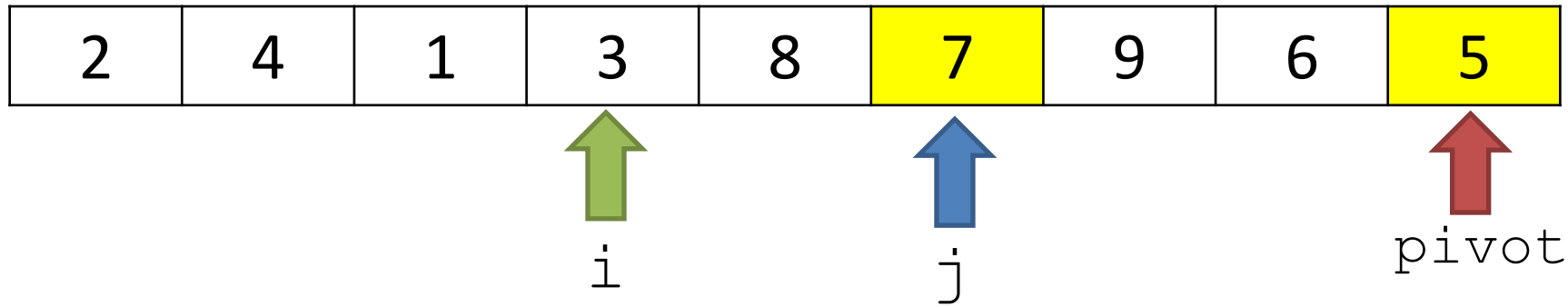


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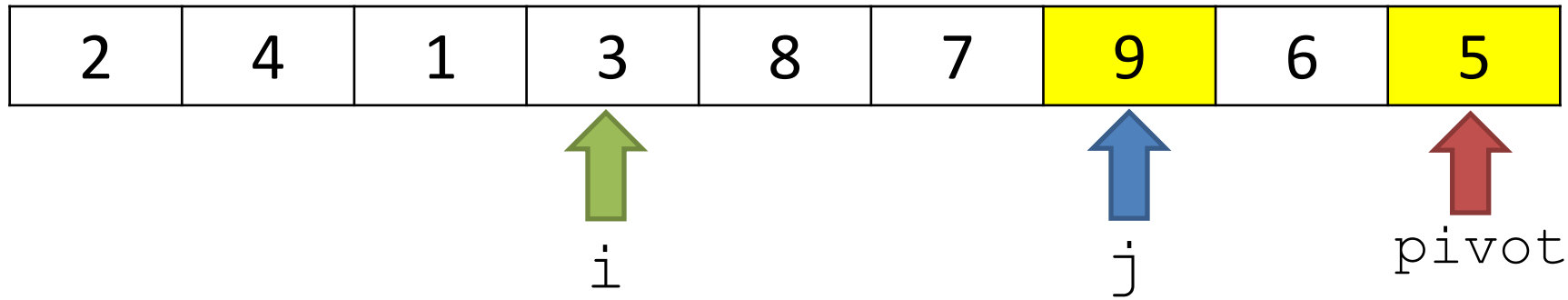


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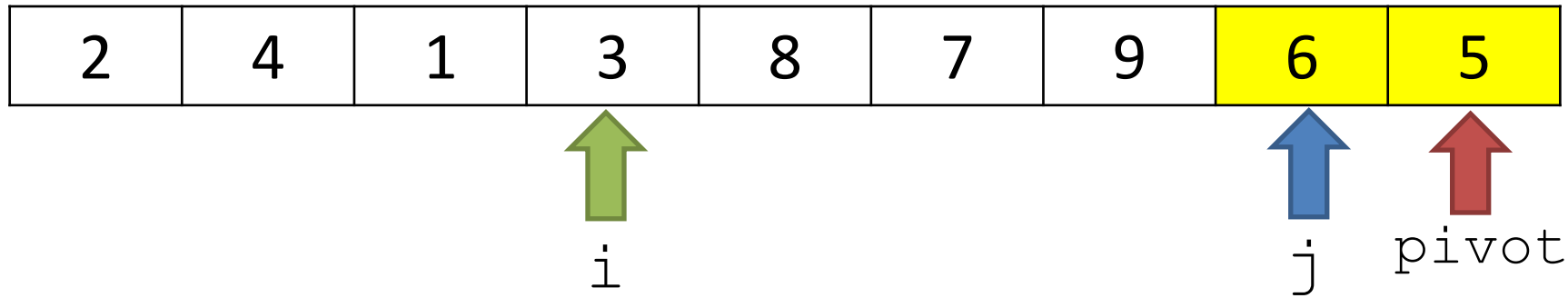


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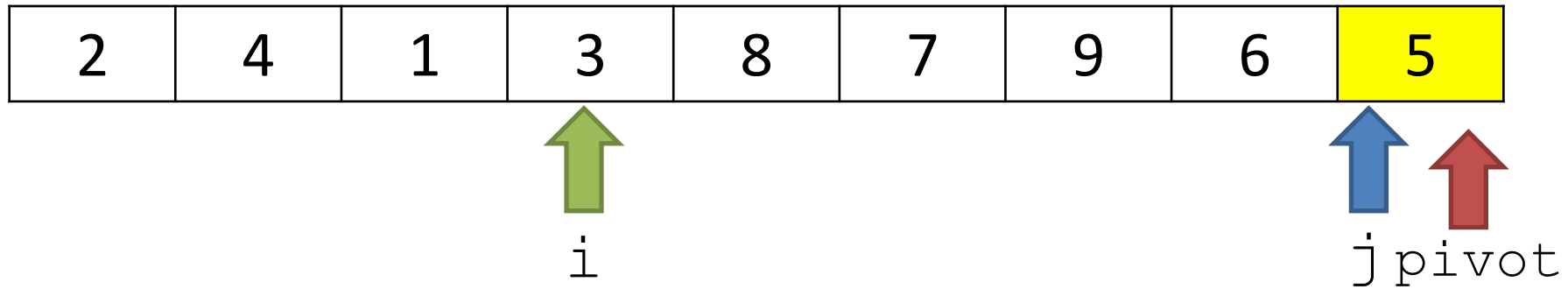


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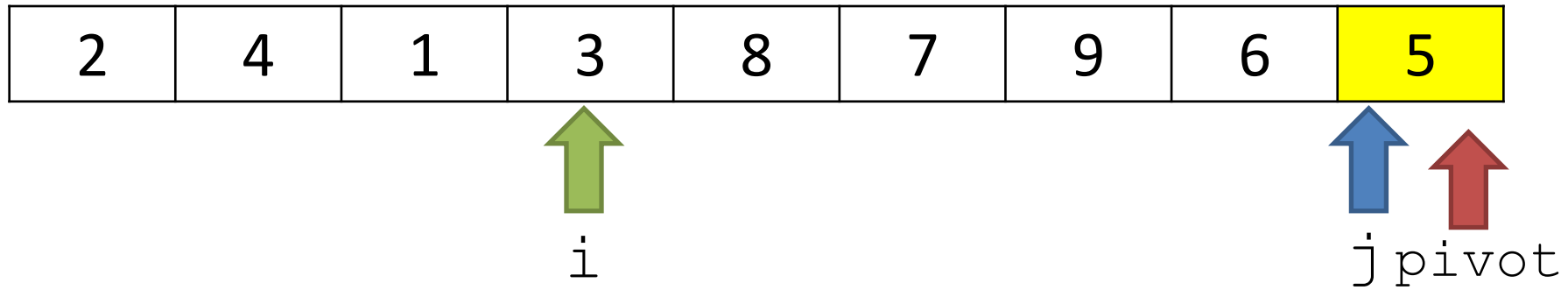


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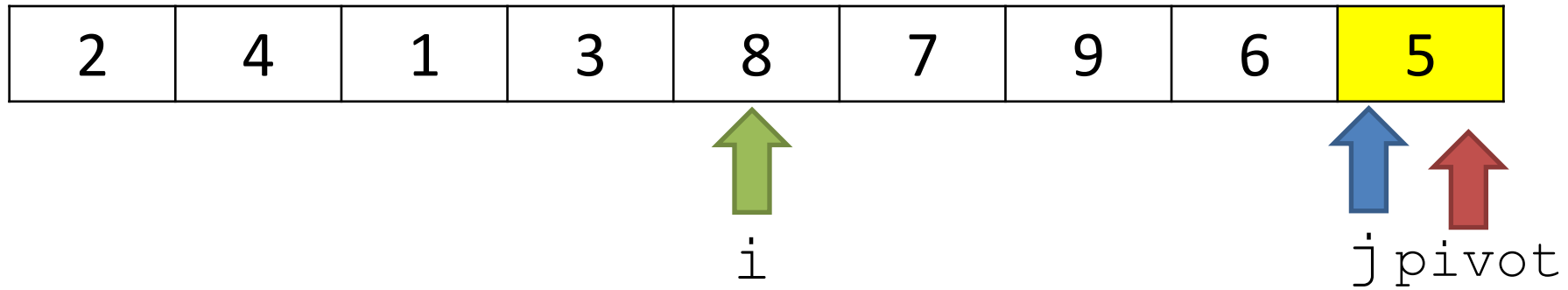
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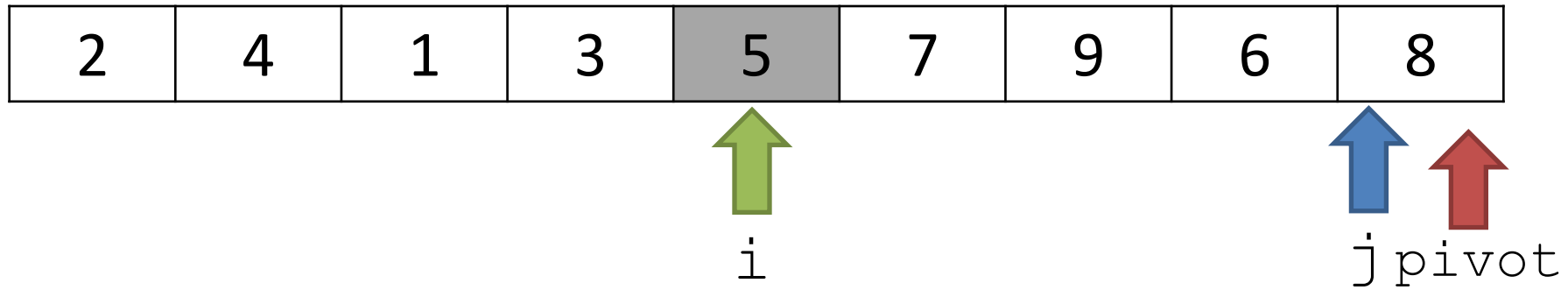
If not, increase j by 1



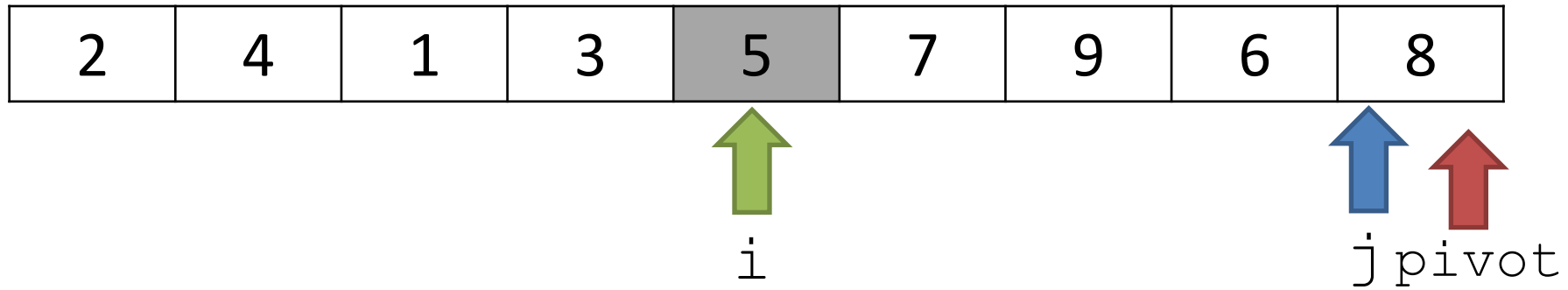
Once j reaches the pivot, we will increase i by 1, and then swap the pivot with the element located at index i



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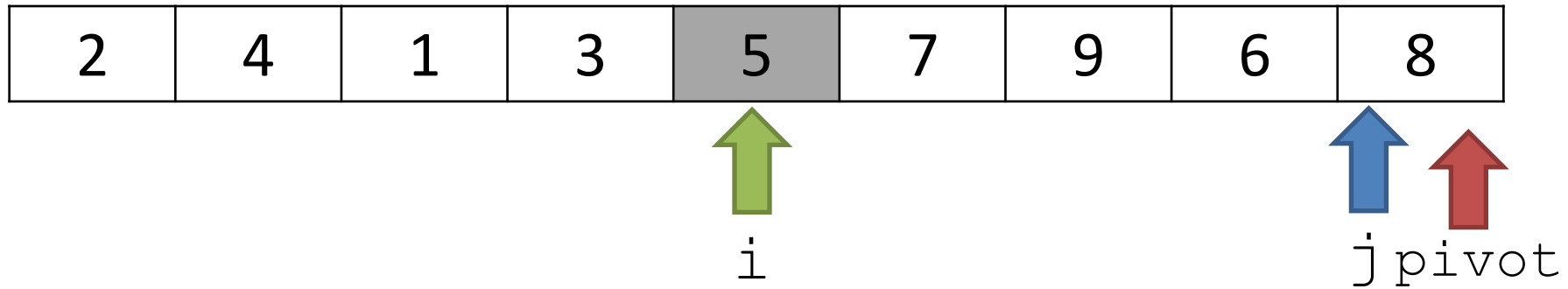


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???



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Our pivot is now in the correct spot!

**Everything to the left is less than the pivot,
everything to the right is greater than the pivot**

2	4	1	3	5	7	9	6	8
---	---	---	---	---	---	---	---	---

This step is known as **partitioning**

2	4	1	3	5	7	9	6	8
---	---	---	---	---	---	---	---	---

Now, we will recursively call `quick_sort` on the left section of the array, and the right section of the array

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---	---	---	---	---	---	---	---	---

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Unlike Merge Sort, these are **not** new arrays, these are just “sections” of the original array

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Due to how we call our recursive methods, we will always prioritize the “left tree” of the array

2	4	1	3	5	7	9	6	8
---	---	---	---	---	---	---	---	---

`quick_sort(`

2	4	1	3
---	---	---	---

)

Now we partition this section!

2	4	1	3	5	7	9	6	8
---	---	---	---	---	---	---	---	---

quick_sort(

2	4	1	3
---	---	---	---



i

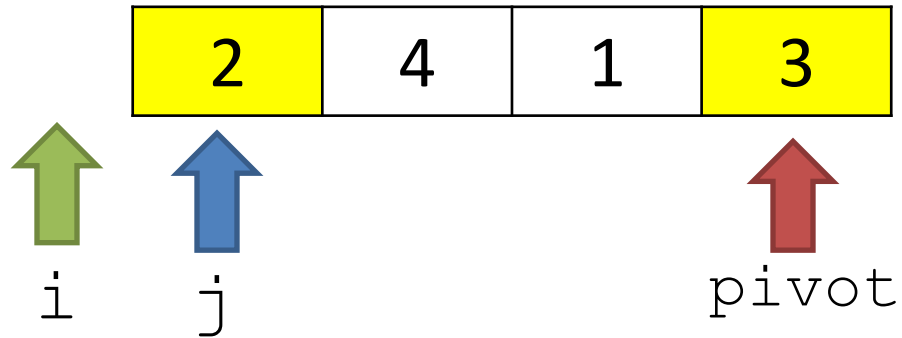


j



pivot

2	4	1	3	5	7	9	6	8
---	---	---	---	---	---	---	---	---



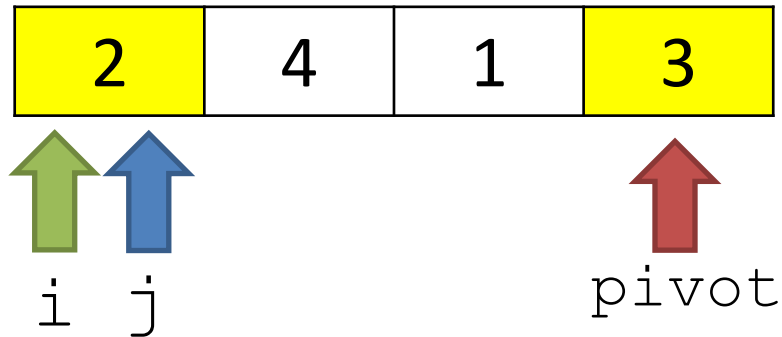
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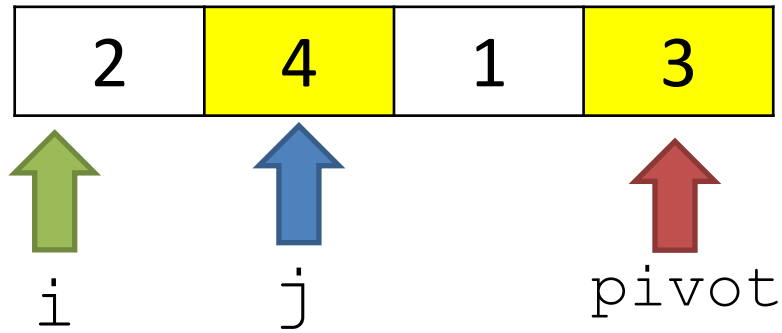
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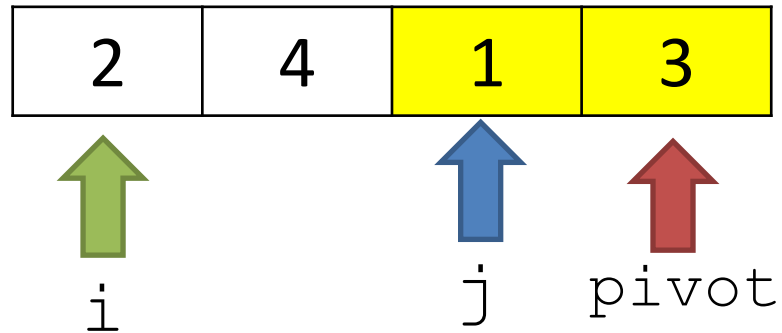
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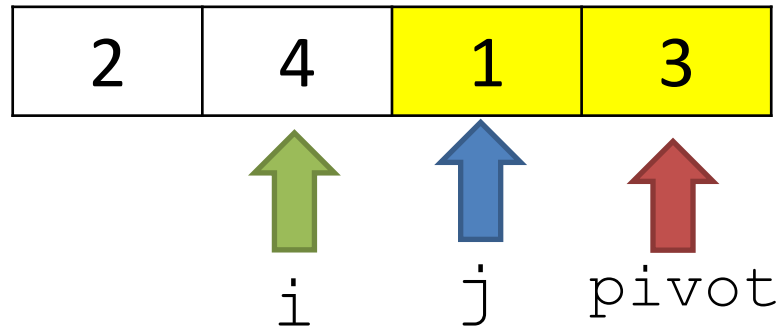
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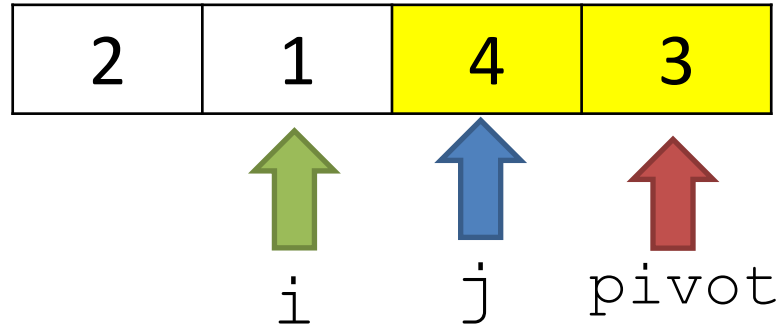
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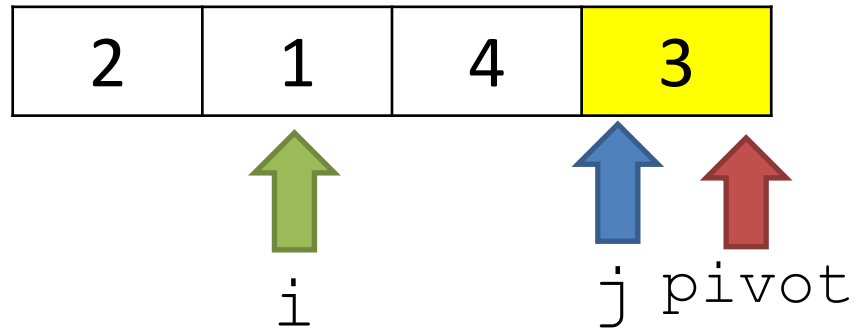
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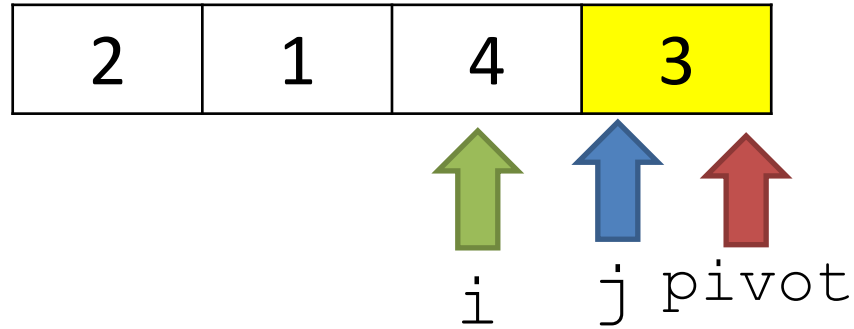
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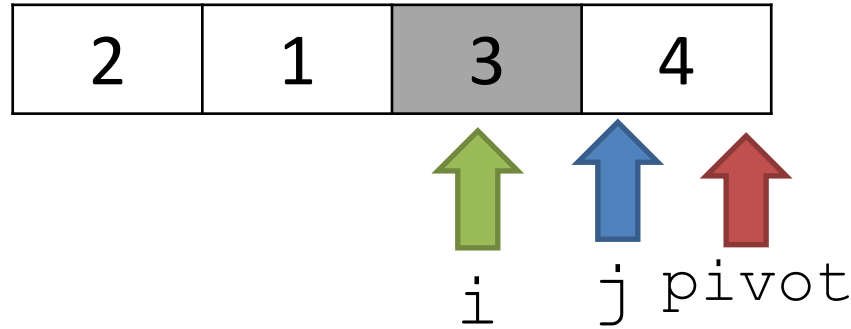
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---	---	---	---	---	---	---	---	---

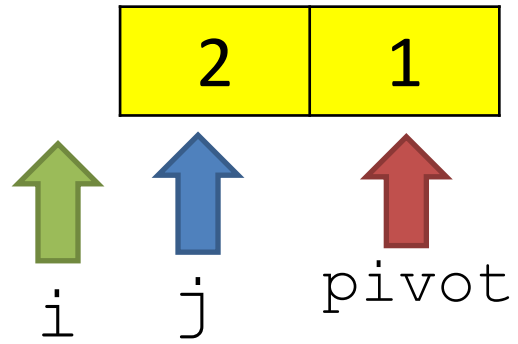
2	1	3	4
---	---	---	---

2	1
---	---

4

2	4	1	3	5	7	9	6	8
---	---	---	---	---	---	---	---	---

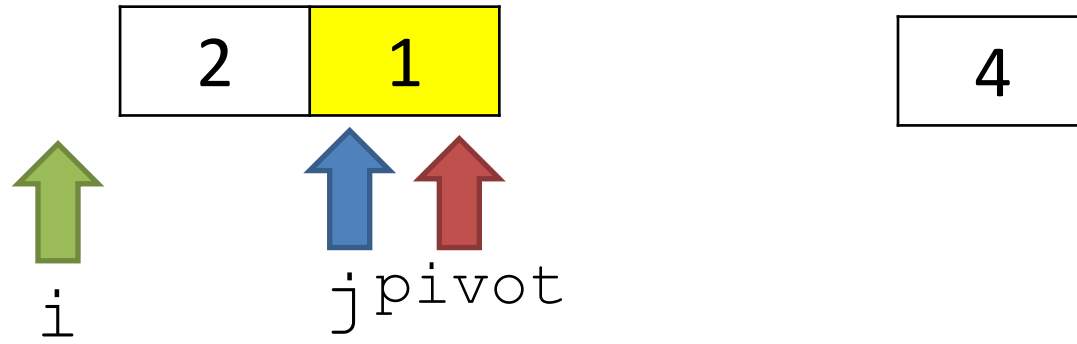
2	1	3	4
---	---	---	---



4

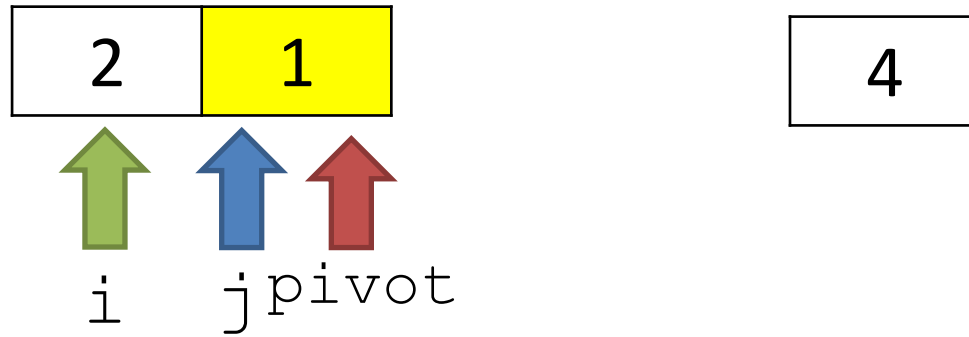
2	4	1	3	5	7	9	6	8
---	---	---	---	---	---	---	---	---

2	1	3	4
---	---	---	---



2	4	1	3	5	7	9	6	8
---	---	---	---	---	---	---	---	---

2	1	3	4
---	---	---	---



2	4	1	3	5	7	9	6	8
---	---	---	---	---	---	---	---	---

2	1	3	4
---	---	---	---

1	2
---	---

4



i j pivot

2	4	1	3	5	7	9	6	8
---	---	---	---	---	---	---	---	---

2	1	3	4
---	---	---	---

1	2
---	---

4

2	4	1	3	5	7	9	6	8
---	---	---	---	---	---	---	---	---

2	1	3	4
---	---	---	---

1	2	4
---	---	---

2

If the size of our “array section” is 1, then it’s already sorted!

2	4	1	3	5	7	9	6	8
---	---	---	---	---	---	---	---	---

2	1	3	4
---	---	---	---

1	2	4
---	---	---

2

If the size of our “array section” is 1, then it’s already sorted!

2	4	1	3	5	7	9	6	8
---	---	---	---	---	---	---	---	---

2	1	3	4
---	---	---	---

1	2
---	---

4

If the size of our “array section” is 1, then it’s already sorted!

2	4	1	3	5	7	9	6	8
---	---	---	---	---	---	---	---	---

1	2	3	4
---	---	---	---

4

If the size of our “array section” is 1, then it’s already sorted!

2	4	1	3	5	7	9	6	8
---	---	---	---	---	---	---	---	---

1	2	3	4
---	---	---	---

4

If the size of our “array section” is 1, then it’s already sorted!

2	4	1	3	5	7	9	6	8
---	---	---	---	---	---	---	---	---

1	2	3	4
---	---	---	---

If the size of our “array section” is 1, then it’s already sorted!

1	2	3	4	5	7	9	6	8
---	---	---	---	---	---	---	---	---

quick_sort(

2	4	1	3
---	---	---	---

)



quick_sort(

7	9	6	8
---	---	---	---

)

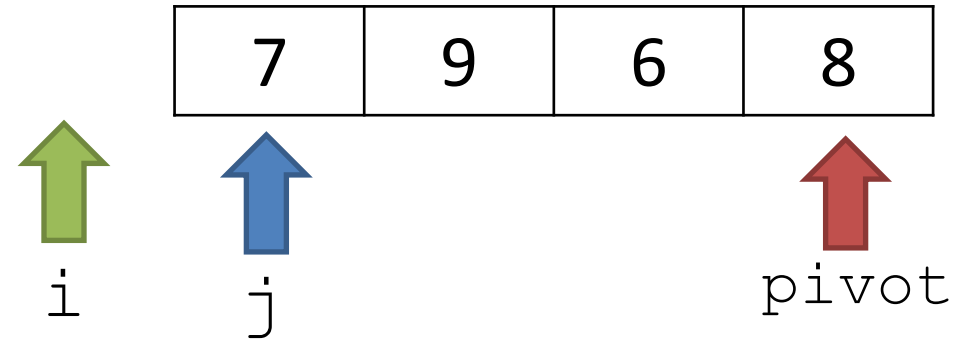
1	2	3	4	5	7	9	6	8
---	---	---	---	---	---	---	---	---

quick_sort(

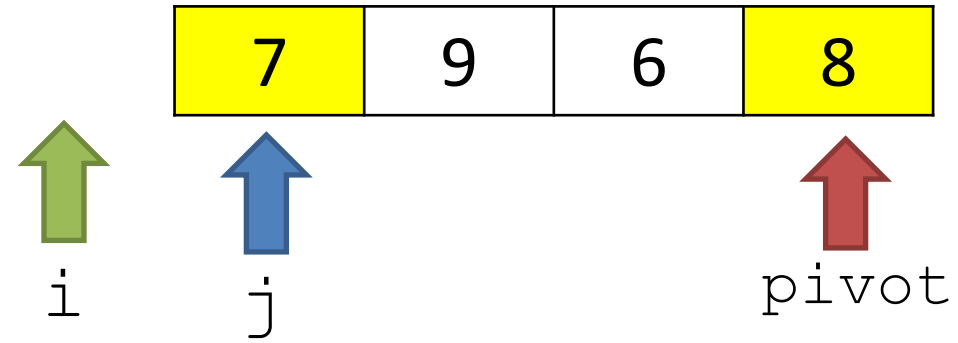
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)

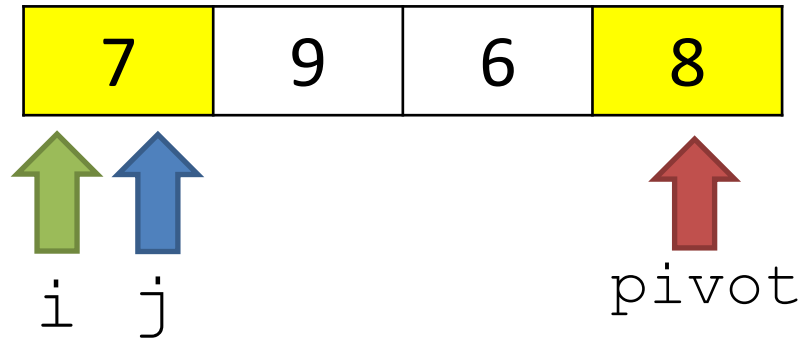
1	2	3	4	5	7	9	6	8
---	---	---	---	---	---	---	---	---



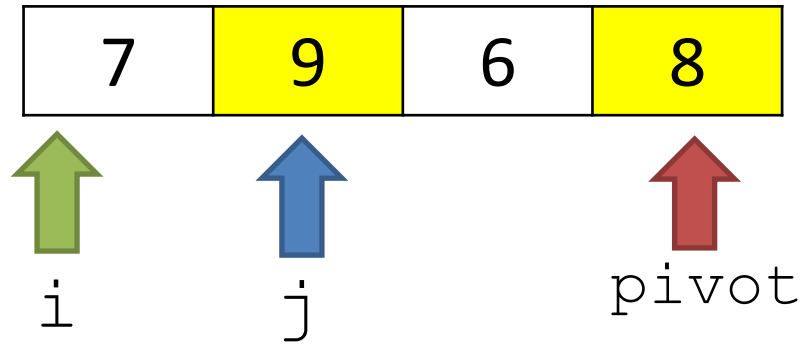
1	2	3	4	5	7	9	6	8
---	---	---	---	---	---	---	---	---



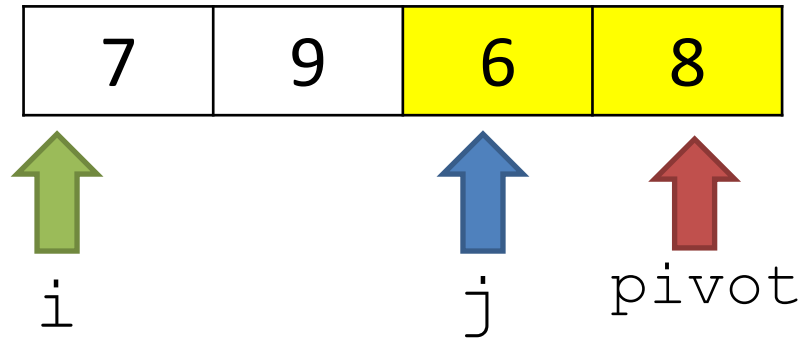
1	2	3	4	5	7	9	6	8
---	---	---	---	---	---	---	---	---



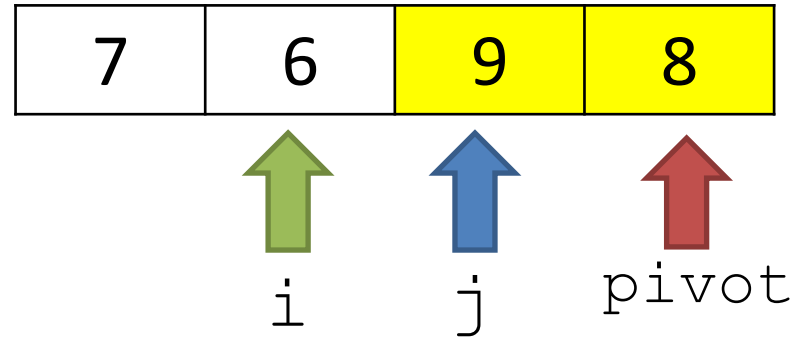
1	2	3	4	5	7	9	6	8
---	---	---	---	---	---	---	---	---



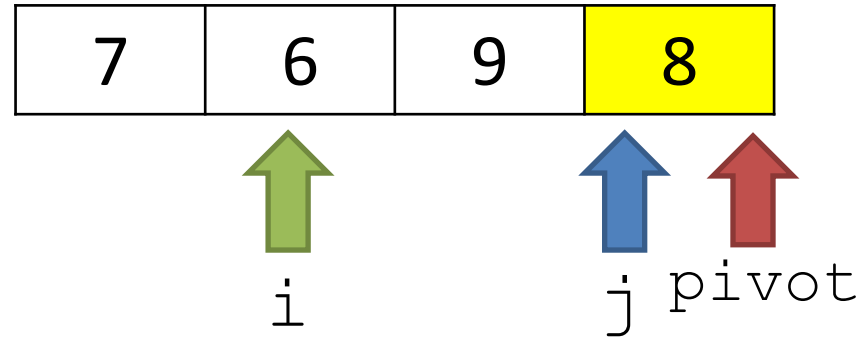
1	2	3	4	5	7	9	6	8
---	---	---	---	---	---	---	---	---



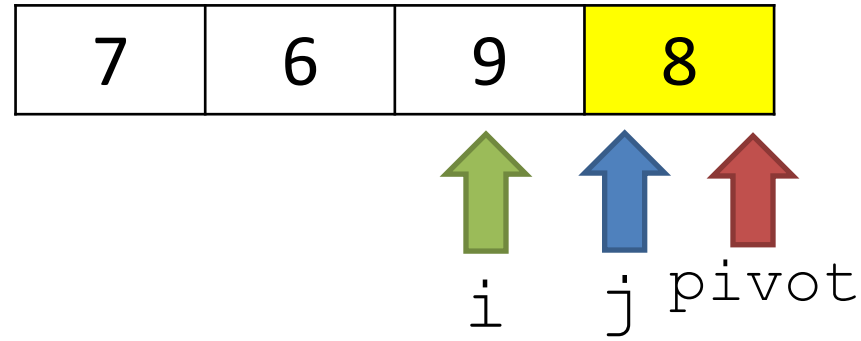
1	2	3	4	5	7	9	6	8
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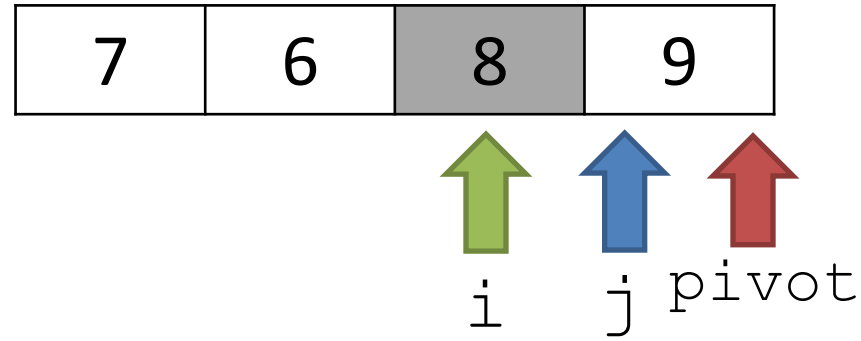
1	2	3	4	5	7	9	6	8
---	---	---	---	---	---	---	---	---



1	2	3	4	5	7	9	6	8
---	---	---	---	---	---	---	---	---



1	2	3	4	5	7	9	6	8
---	---	---	---	---	---	---	---	---



1	2	3	4	5	7	9	6	8
---	---	---	---	---	---	---	---	---

7	6	8	9
---	---	---	---

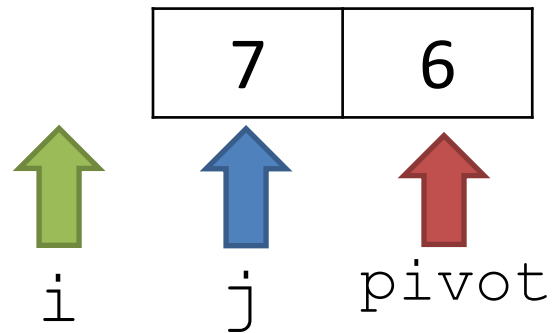
7	6
---	---

9

Call quick sort, and give it the section of the array to the left of the pivot, and to the right of the pivot

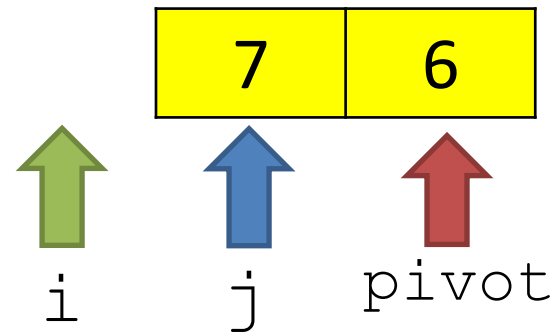
1	2	3	4	5	7	9	6	8
---	---	---	---	---	---	---	---	---

7	6	8	9
---	---	---	---



1	2	3	4	5	7	9	6	8
---	---	---	---	---	---	---	---	---

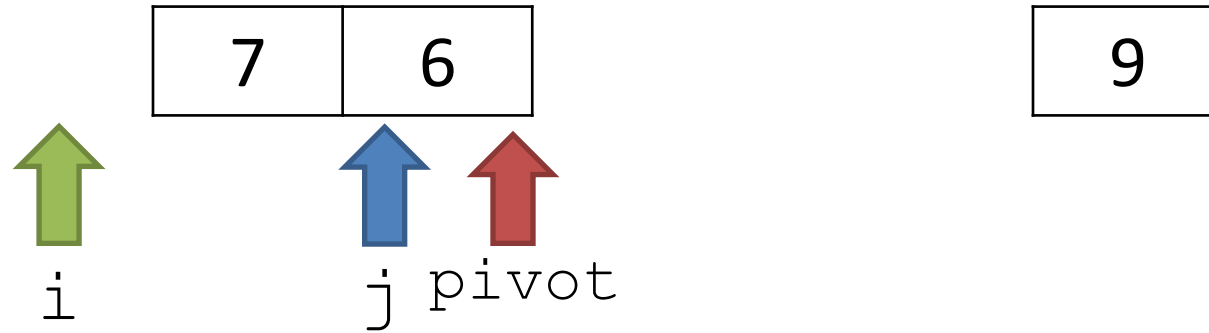
7	6	8	9
---	---	---	---



9

1	2	3	4	5	7	9	6	8
---	---	---	---	---	---	---	---	---

7	6	8	9
---	---	---	---



1	2	3	4	5	7	9	6	8
---	---	---	---	---	---	---	---	---

7	6	8	9
---	---	---	---

7	6
---	---

9



i



j






pivot

1	2	3	4	5	7	9	6	8
---	---	---	---	---	---	---	---	---

7	6	8	9
---	---	---	---

6	7
---	---

9


 i

 j

 pivot

1	2	3	4	5	7	9	6	8
---	---	---	---	---	---	---	---	---

7	6	8	9
---	---	---	---

6	7
---	---

9

7

1	2	3	4	5	7	9	6	8
---	---	---	---	---	---	---	---	---

7	6	8	9
---	---	---	---

6	7
---	---

9

7

1	2	3	4	5	7	9	6	8
---	---	---	---	---	---	---	---	---

7	6	8	9
---	---	---	---

6	7
---	---

9

1	2	3	4	5	7	9	6	8
---	---	---	---	---	---	---	---	---

6	7	8	9
---	---	---	---

9

1	2	3	4	5	7	9	6	8
---	---	---	---	---	---	---	---	---

6	7	8	9
---	---	---	---

9

1	2	3	4	5	7	9	6	8
---	---	---	---	---	---	---	---	---

6	7	8	9
---	---	---	---

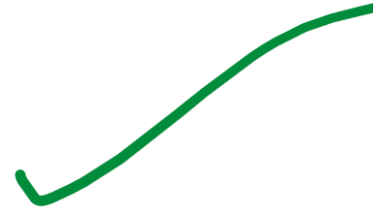
1	2	3	4	5	6	7	8	9
---	---	---	---	---	---	---	---	---

All done!!



1	2	3	4	5	6	7	8	9
---	---	---	---	---	---	---	---	---

All done!!



Let's code this!!!

```
public static int[] quick_sort(int[] array, int start, int end) {  
    if(end <= start) { //base case: array is size 1 or nothing  
        return array;  
    }  
    int pivot = partition(array, start, end);  
    quick_sort(array, start, pivot-1);  
    quick_sort(array, pivot + 1, end);  
    return array;  
}
```

```
public static int partition(int[] array, int start, int end) {  
    int pivot = array[end];  
    int i = start - 1;  
    for(int j = start; j <= end - 1; j++) {  
        if(array[j] < pivot) {  
            i++;  
            int temp = array[i];  
            array[i] = array[j];  
            array[j] = temp;  
        }  
    }  
}
```

```
public static int[] quick_sort(int[] array, int start, int end) {  
    if(end <= start) { //base case: array is size 1 or nothing  
        return array;  
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        if(array[j] < pivot) {  
            i++;  
            int temp = array[i];  
            array[i] = array[j];  
            array[j] = temp;  
        }  
    }  
}
```

Running time?


```

public static int[] quick_sort(int[] array, int start, int end) {
    if(end <= start) { //base case: array is size 1 or nothing
        return array;
    }
    int pivot = partition(array, start, end);
    quick_sort(array, start, pivot-1);
    quick_sort(array, pivot + 1, end);
    return array;
}

```

```

public static int partition(int[] array, int start, int end) {
    int pivot = array[end]; O(1)
    int i = start - 1; O(1)
    for(int j = start; j <= end - 1; j++) { O(n)
        if(array[j] < pivot) { O(1)
            i++; O(1)
            int temp = array[i]; O(1)
            array[i] = array[j]; O(1)
            array[j] = temp; O(1)
        }
    }
}

```

```

public static int[] quick_sort(int[] array, int start, int end) {
    if(end <= start) { //base case: array is size 1 or nothing
        return array;
    }
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    for(int j = start; j <= end - 1; j++) { O(n)
        if(array[j] < pivot) { O(1)
            i++; O(1)
            int temp = array[i]; O(1)
            array[i] = array[j]; O(1)
            array[j] = temp; O(1)
        }
    }
}

```

Running time of partition subroutine = $O(n)$ where n = # of elements in array

```

public static int[] quick_sort(int[] array, int start, int end) {
    if(end <= start) { //base case: array is size 1 or nothing O(1)
        return array; O(1)
    }
    int pivot = partition(array, start, end); O(n)
    quick_sort(array, start, pivot-1); O(1)
    quick_sort(array, pivot + 1, end); O(1)
    return array; O(1)
}

```

Running time of quick sort method = $O(n)$

```

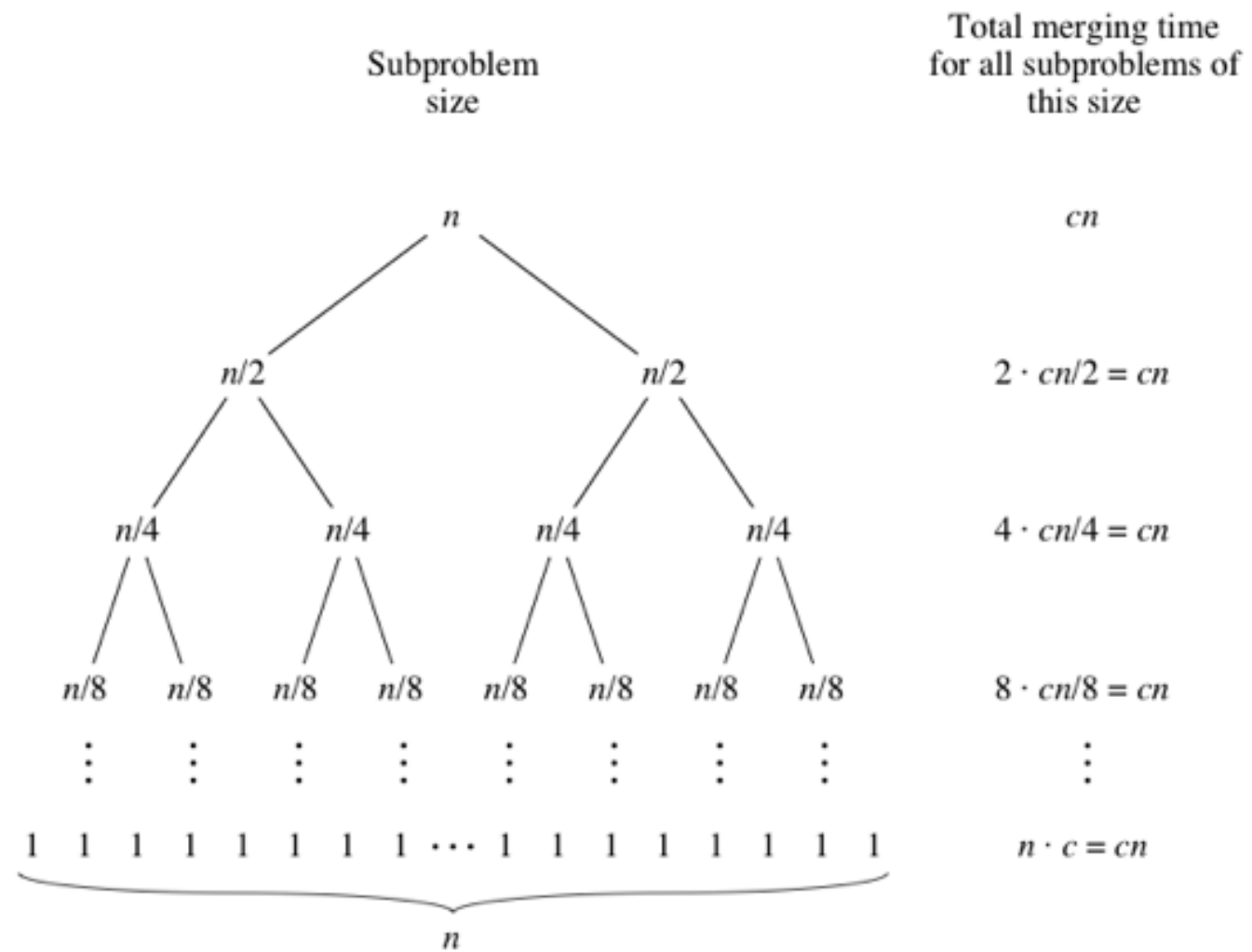
public static int partition(int[] array, int start, int end) {
    int pivot = array[end]; O(1)
    int i = start - 1; O(1)
    for(int j = start; j <= end - 1; j++) { O(n)
        if(array[j] < pivot) { O(1)
            i++; O(1)
            int temp = array[i]; O(1)
            array[i] = array[j]; O(1)
            array[j] = temp; O(1)
        }
    }
}

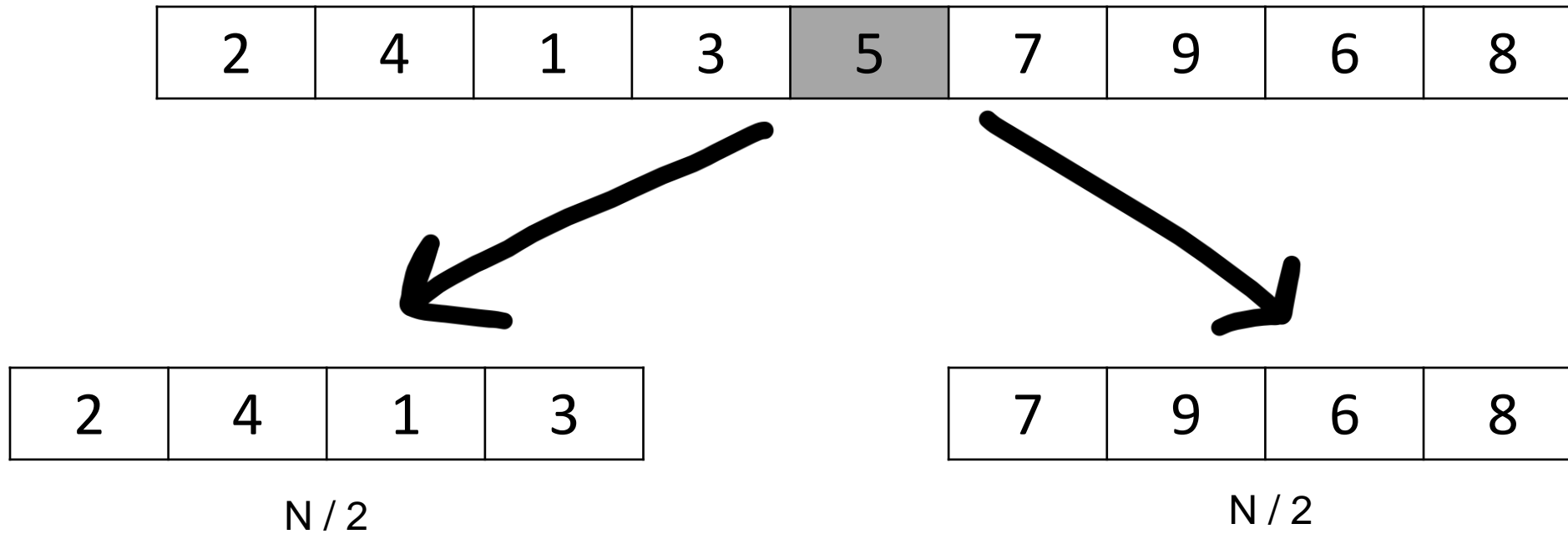
```

Running time of partition subroutine = $O(n)$ where n = # of elements in array

We must now evaluate how often we recursively call the method, and the size of the problem we give that method

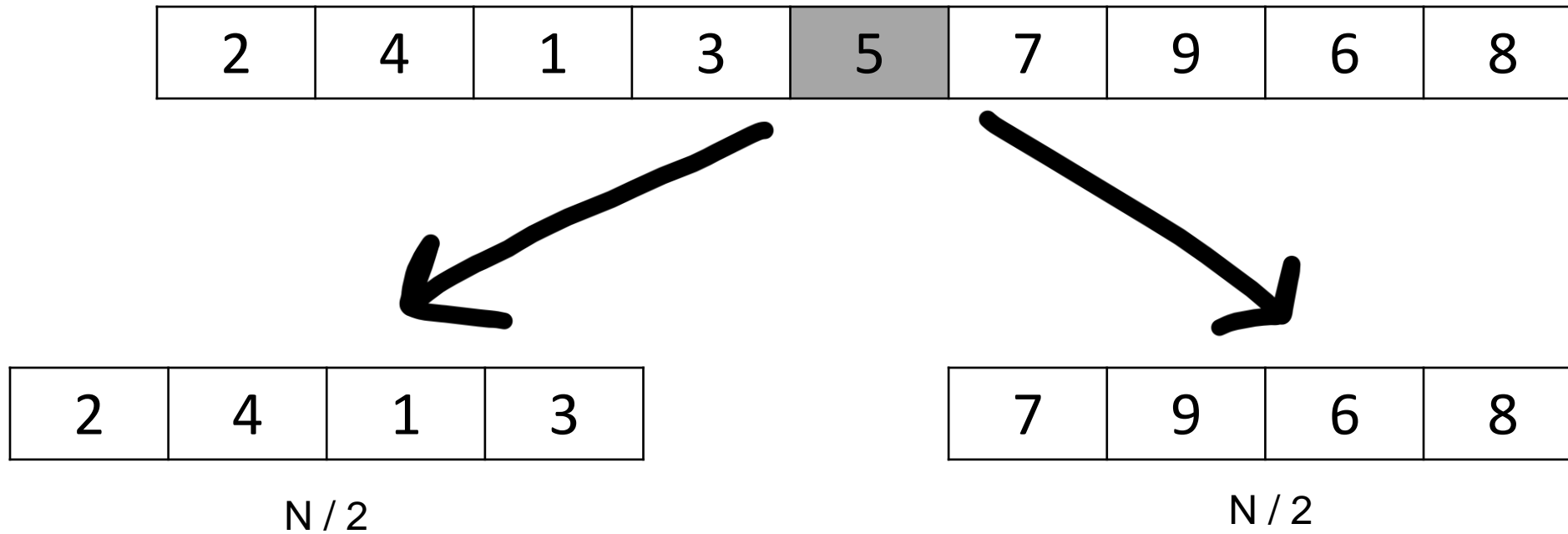
Reminder: Recursion tree for **merge sort**



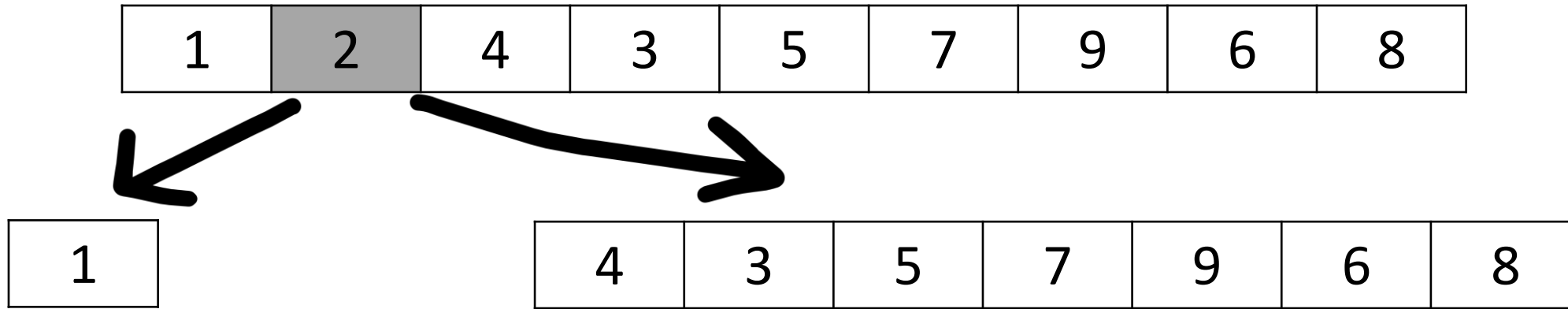


Ideally, we want **balanced** partitions.

That way we are dividing the problem size by 2 (which gives us $\log n$ running time!)

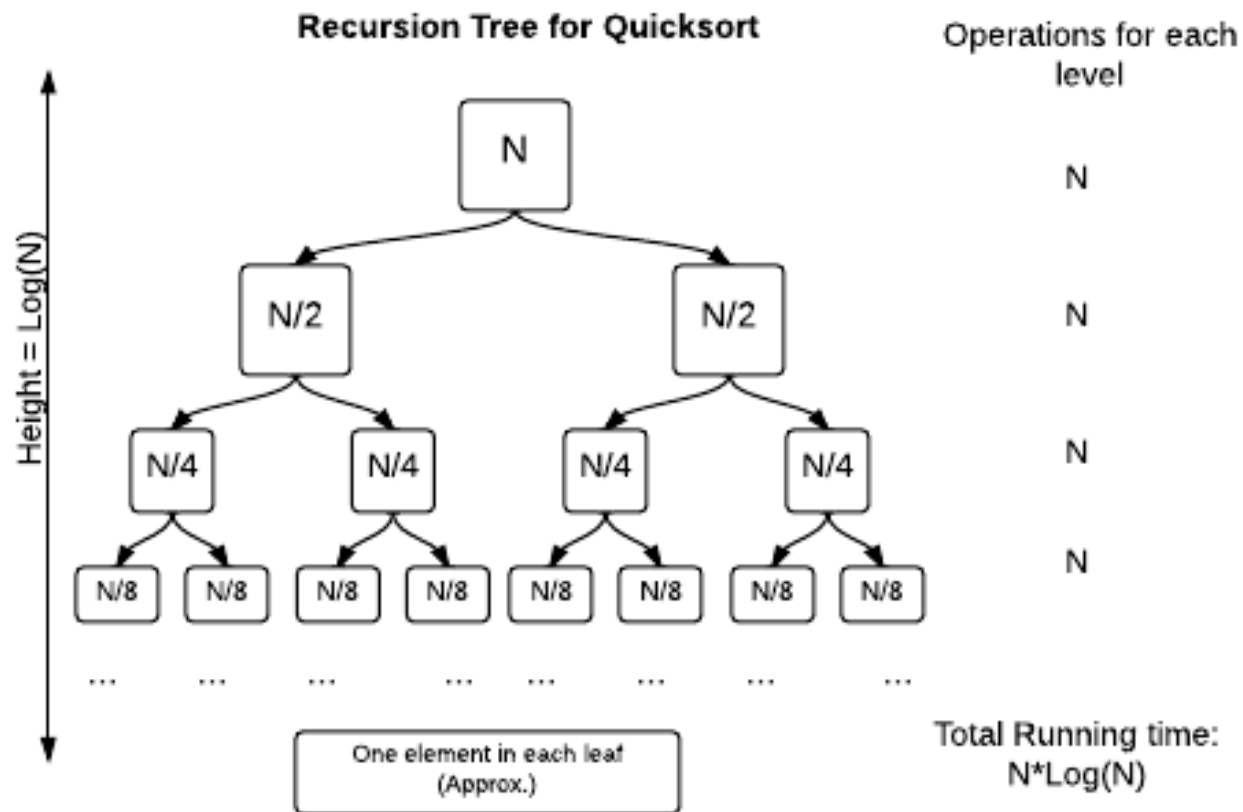


Because our array is random, we don't know how balanced our partitions will be



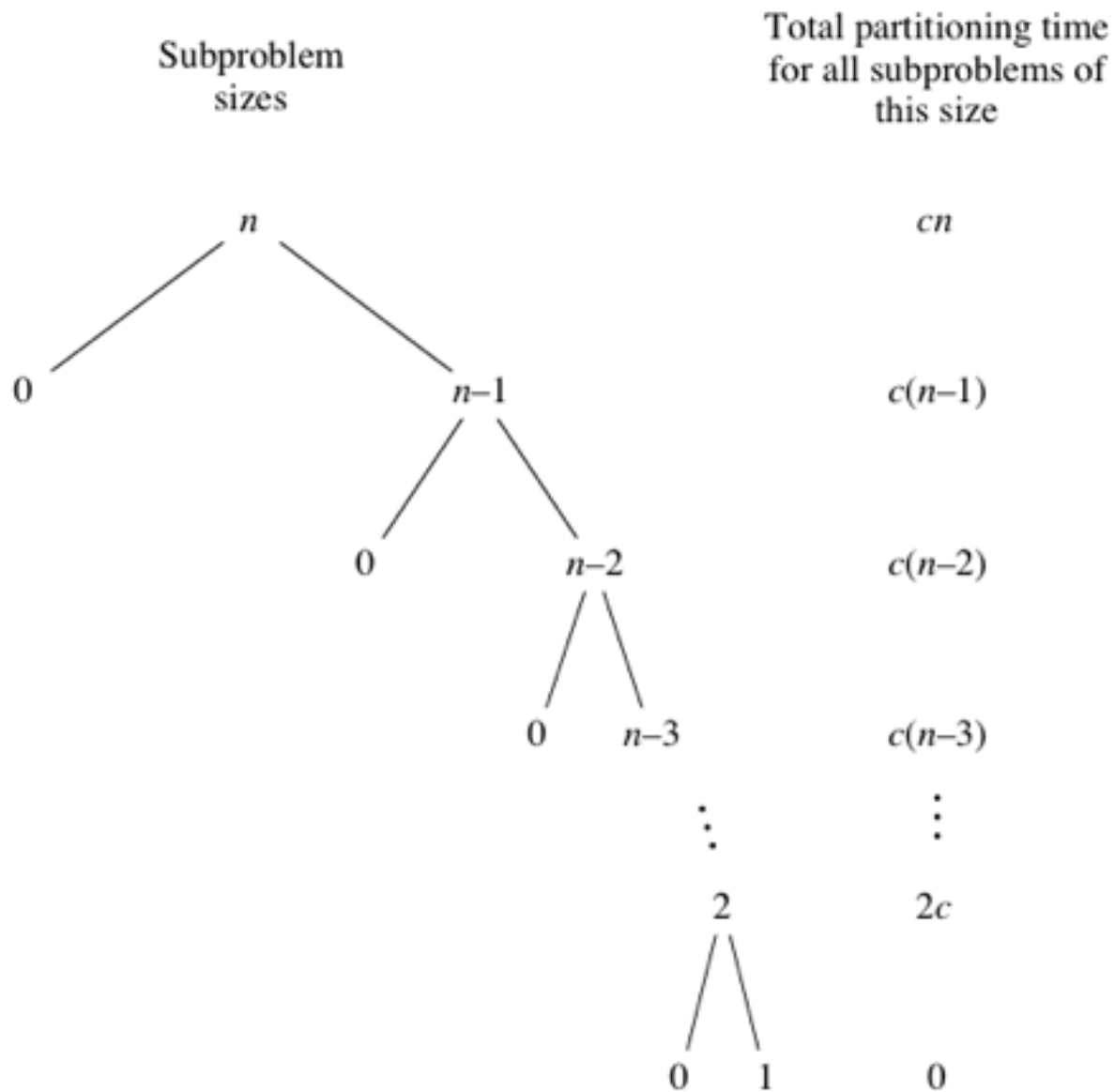
Because our array is random, we don't know how balanced our partitions will be

(This is a less ideal case)



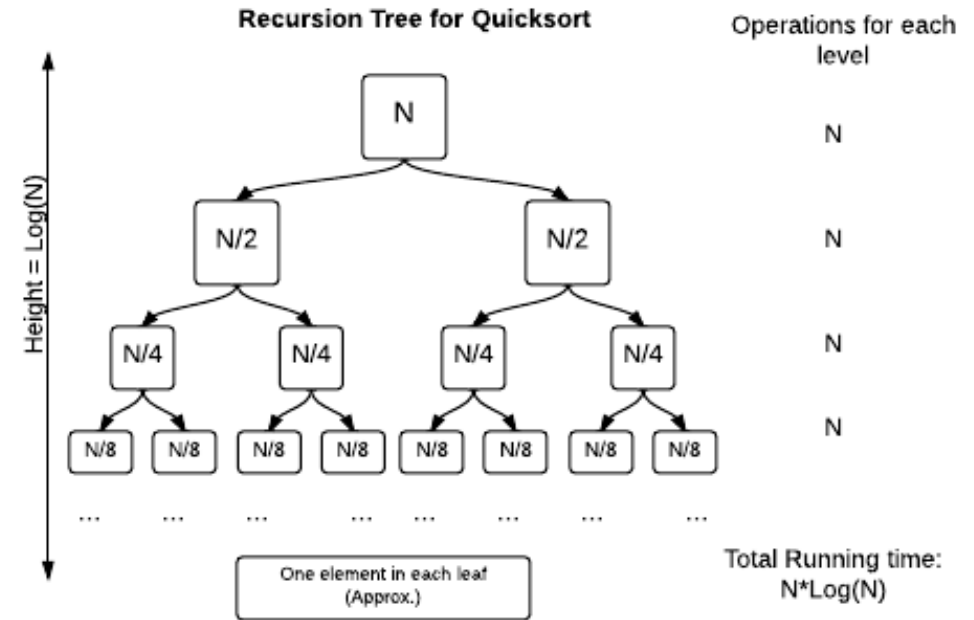
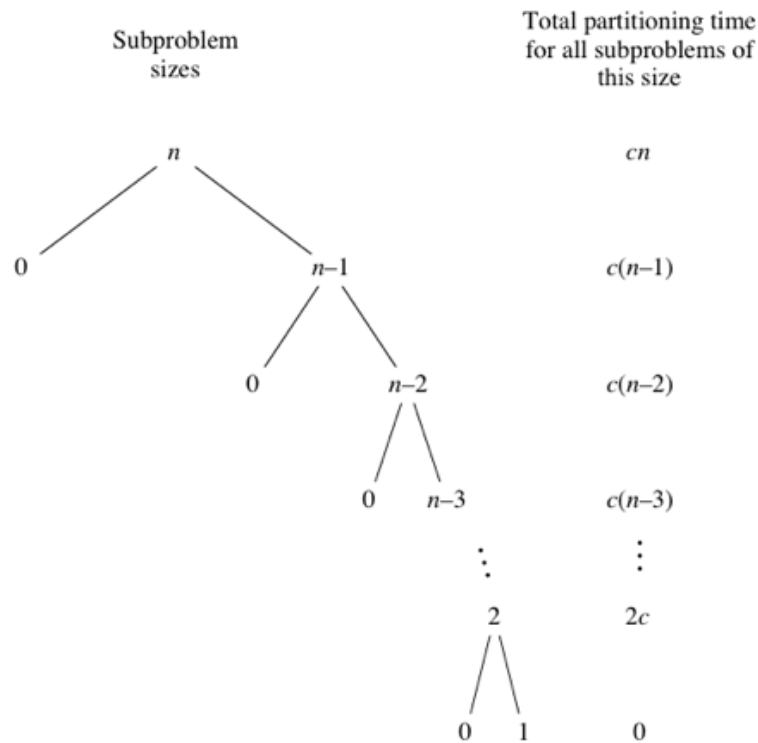
This is the ideal situation...

This will give us **$O(N \cdot \log(n))$** running time

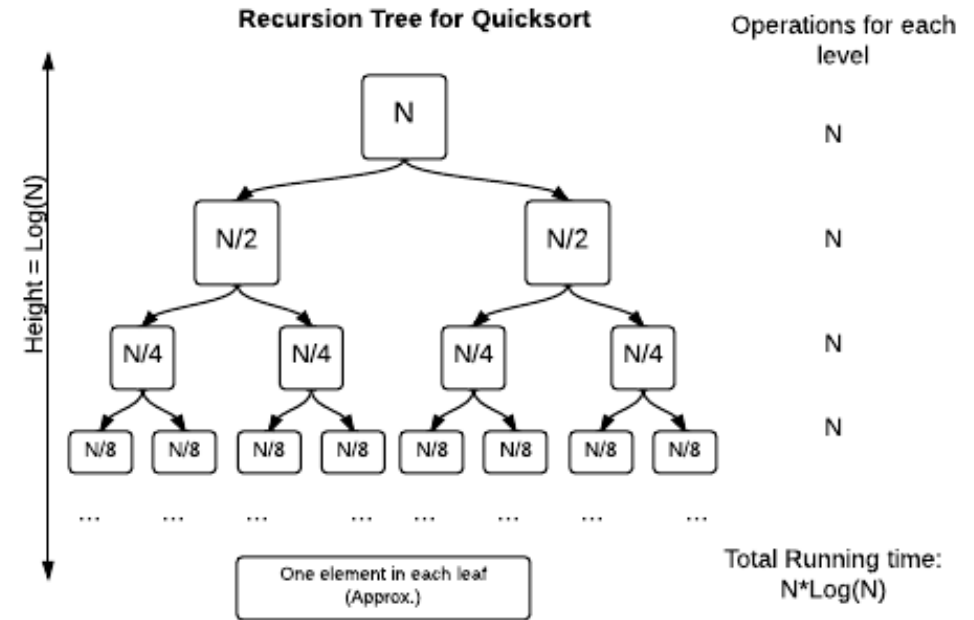
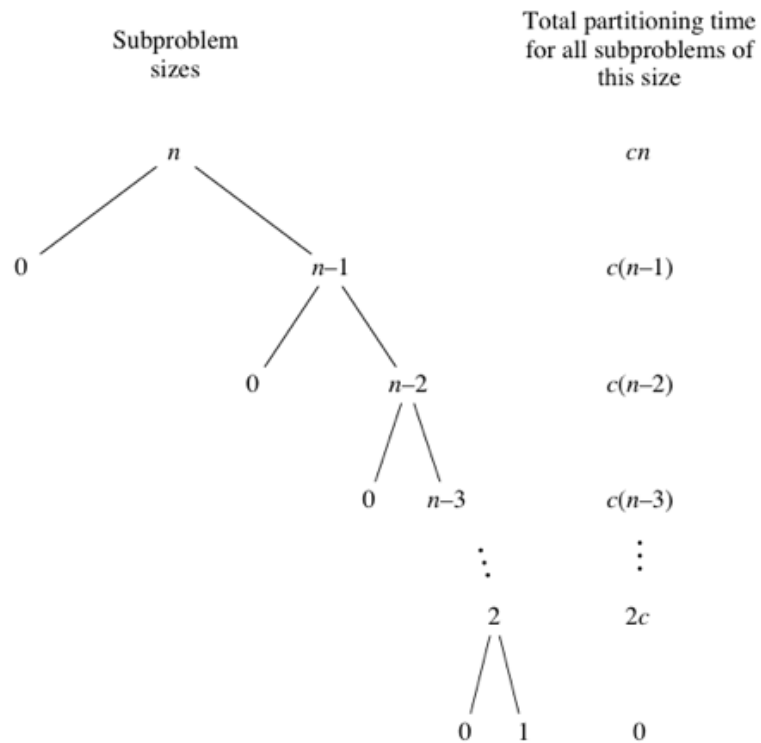


This is worst case scenario...

This will give us **$O(N^2)$** running time



If we select the **median** value of the array as the pivot, that will always give us the optimal recursion tree and **$O(n \log n)$** running time



If we select a **random value** as the pivot, that will actually give us a much better chance of **$O(n \log n)$** running time

Running time of Quick Sort

$O(n^2)$ worse case scenario (n recursive calls, $O(n)$ work at each level)

$O(n * \log n)$ on average (logn recursive calls, $O(n)$ work at each level)