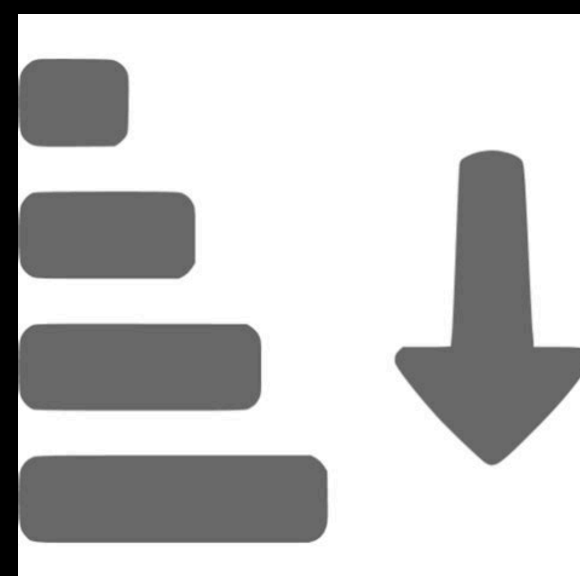
Sorting



Tiziana Ligorio
Hunter College of The City University of New York

Announcements

No tech-prep workshop today

We will resume next week

Plagiarism

Plagiarism is a serious problem

- It seriously damages your future ability to have a successful career

Why do we care?

- Your passing the course is an achievement that reflects your mastery of certain knowledge and skills

- If you plagiarize your way through college, that correlation no longer holds and **our degree becomes meaningless**

- There are many students doing hard work and achieving great results, and we **owe it to them that their degree will be regarded with respect**

Today's Plan

Recap

Sorting algorithms and their analysis

Recap

- Linear search O(n)
- Binary search O(logn)

Sorting

Rearranging a sequence into increasing (decreasing) order!

Several approaches

Can do it in many ways

What is the best way?

Let's find out using Big-O

Last Time Lecture Activity

Write **pseudocode** to sort an array.

543	3	523	76	200	158	195	108	43	274	100	14	599

Find your algorithm, I will ask you about it soon!!!

There are many approaches to sorting
We will look at some comparison-based approaches here

Selection Sort

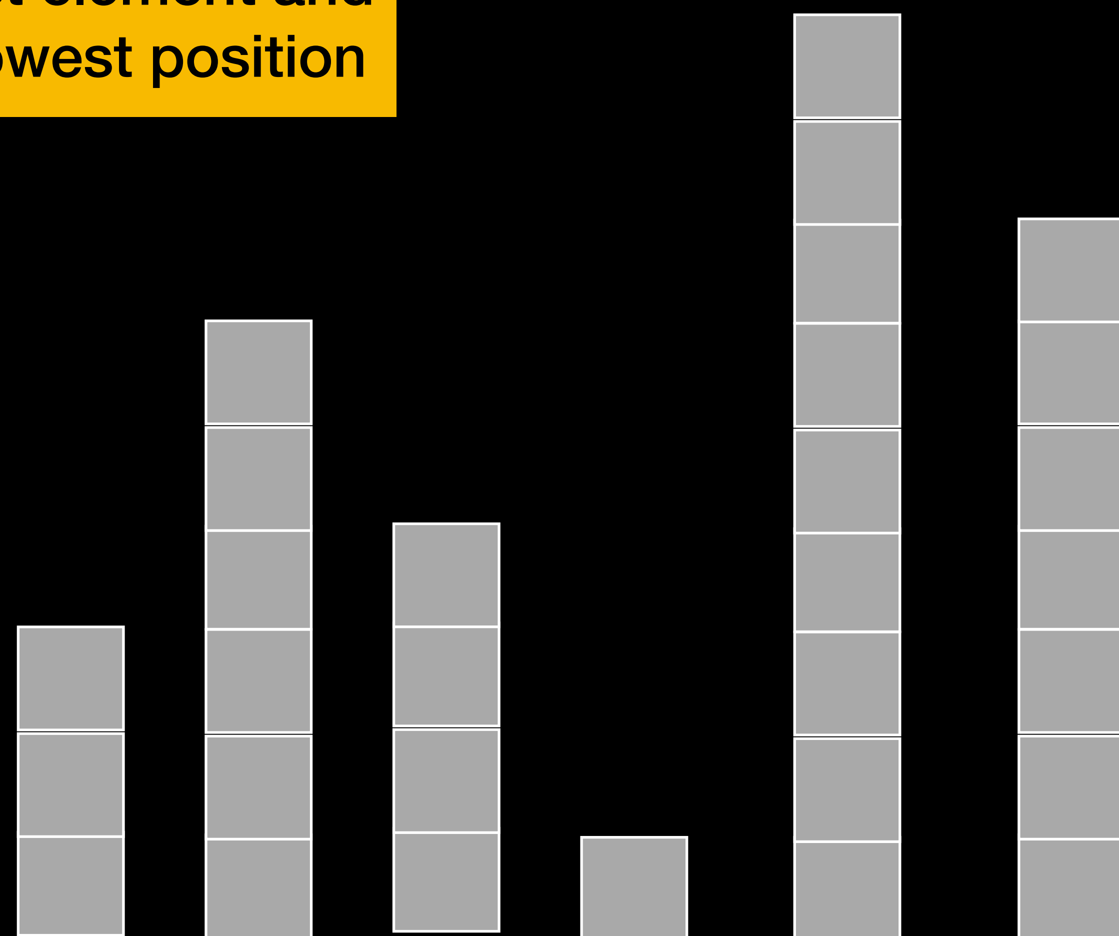
Selection Sort

Unsorted

Sorted

Find smallest element and move it at lowest position

1st Pass



Selection Sort

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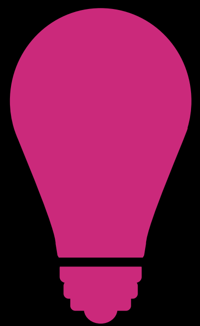

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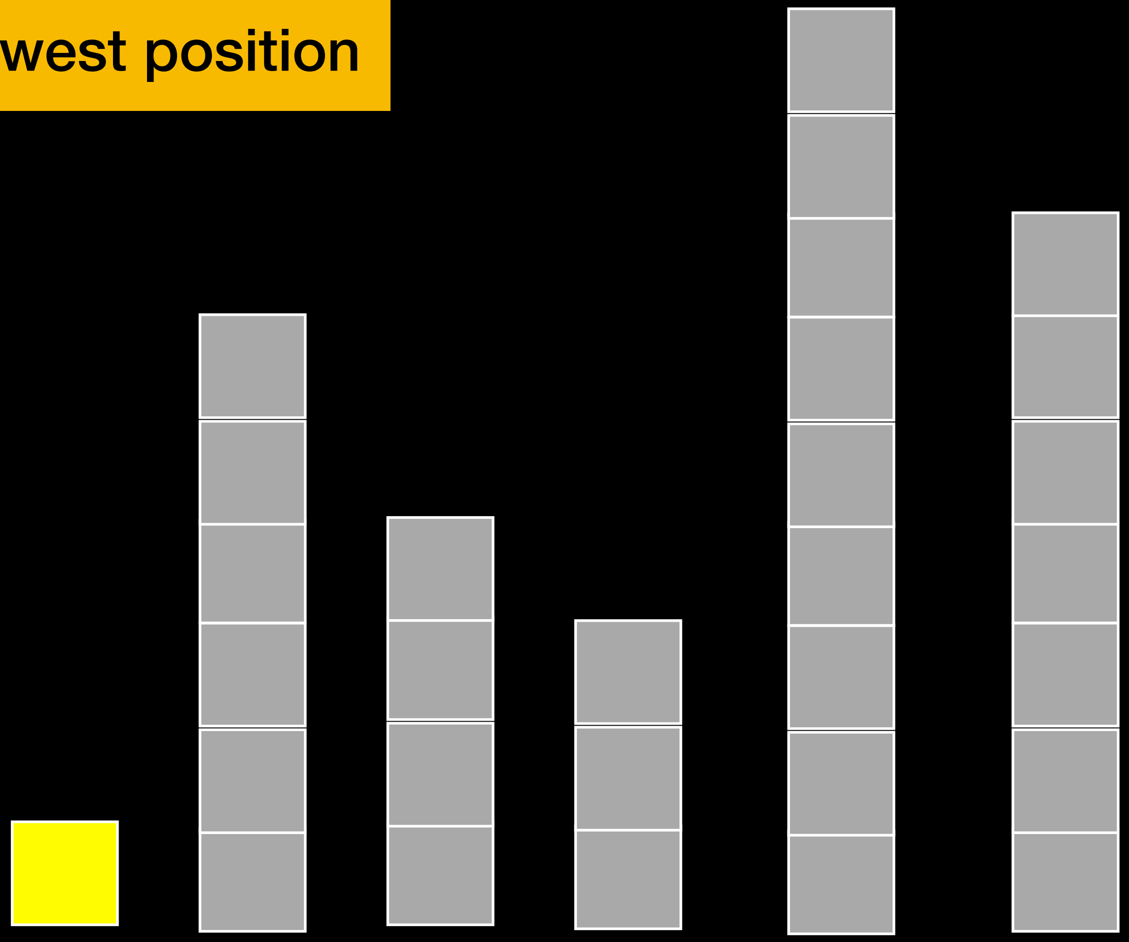
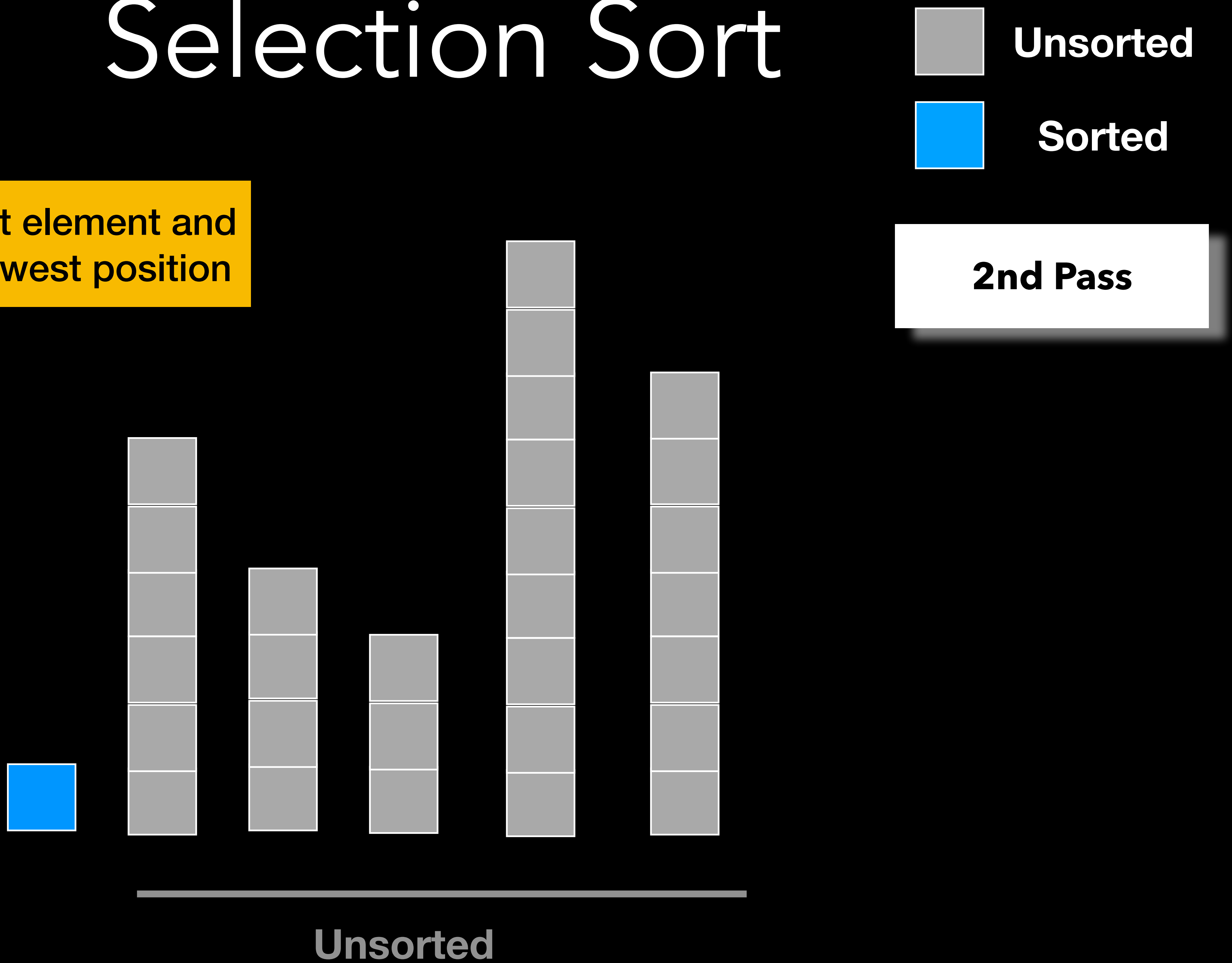


Selection Sort

Find smallest element and move it at lowest position



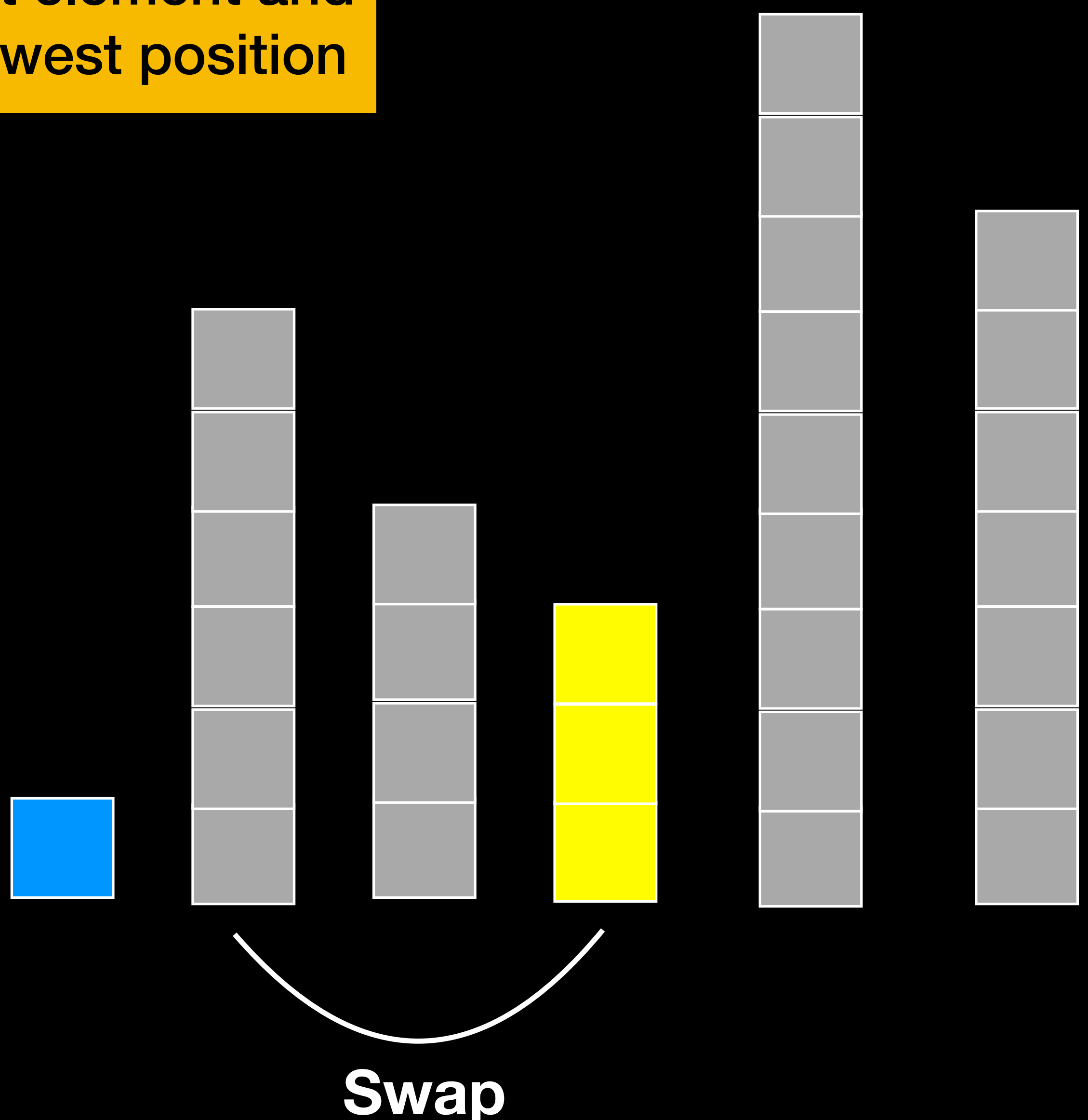
Selection Sort

Unsorted

Sorted

Find smallest element and move it at lowest position

2nd Pass



Selection Sort

Unsorted

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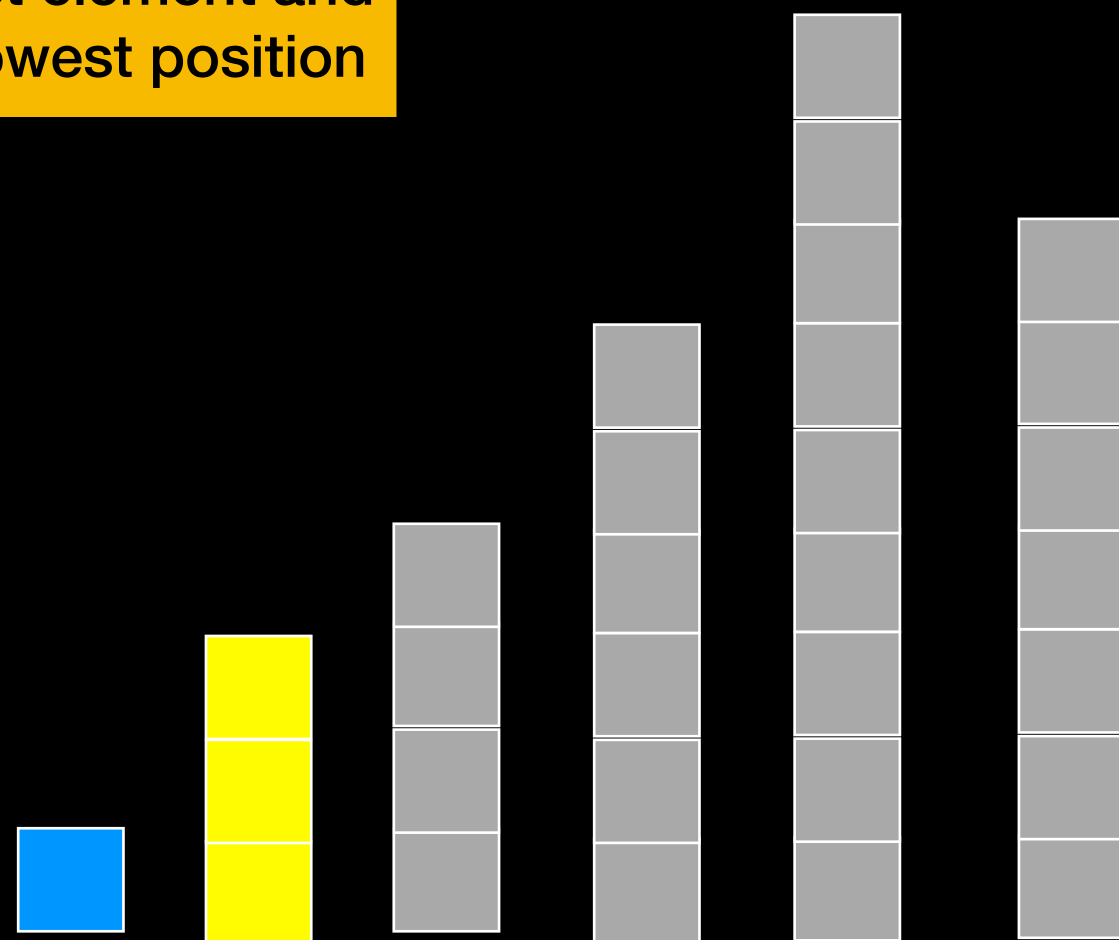
2nd Pass



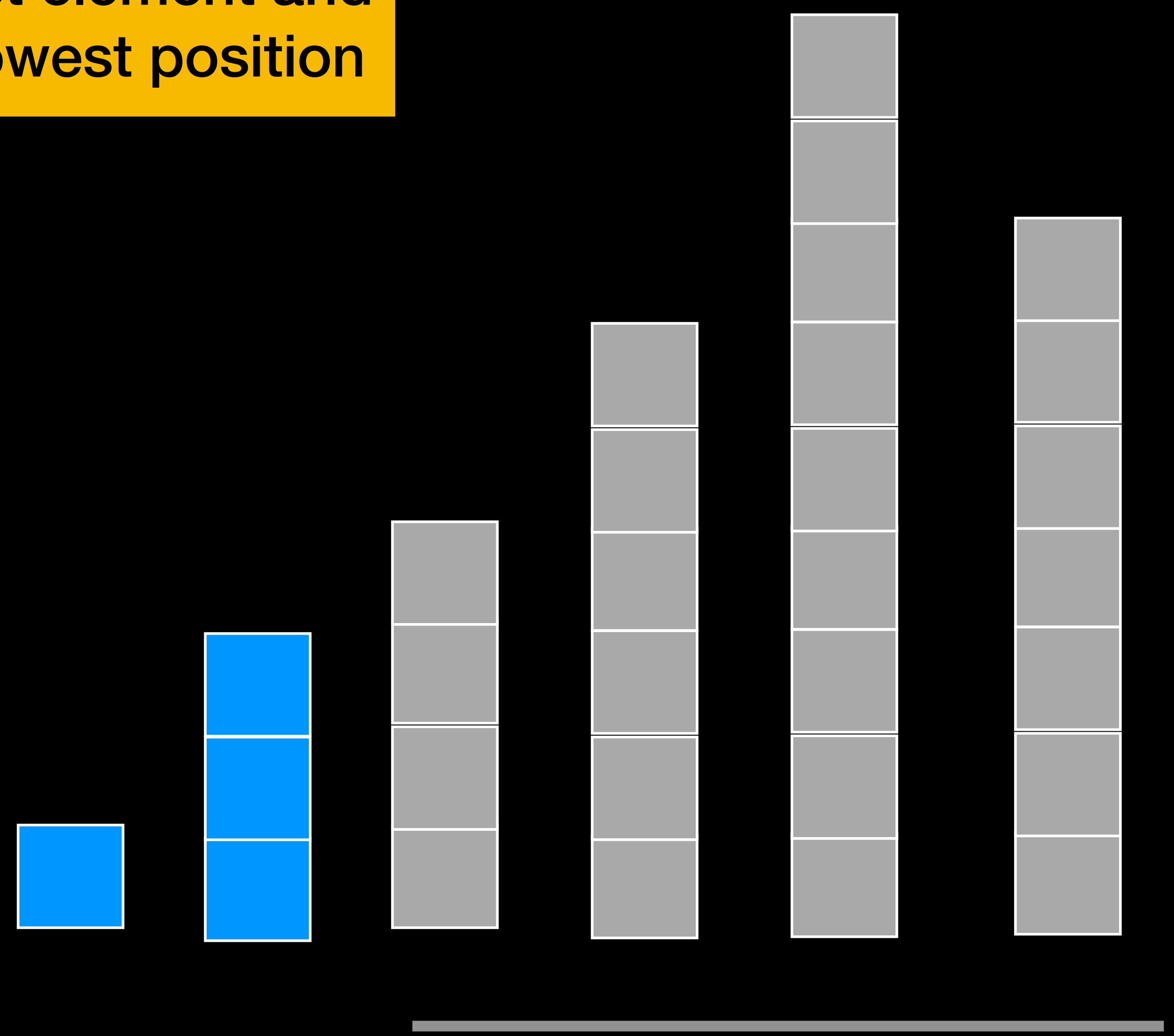
Selection Sort

Unsorted

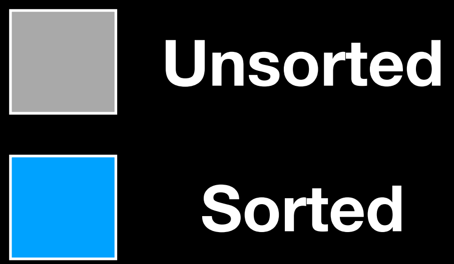
Sorted

Find smallest element and move it at lowest position

3rd Pass

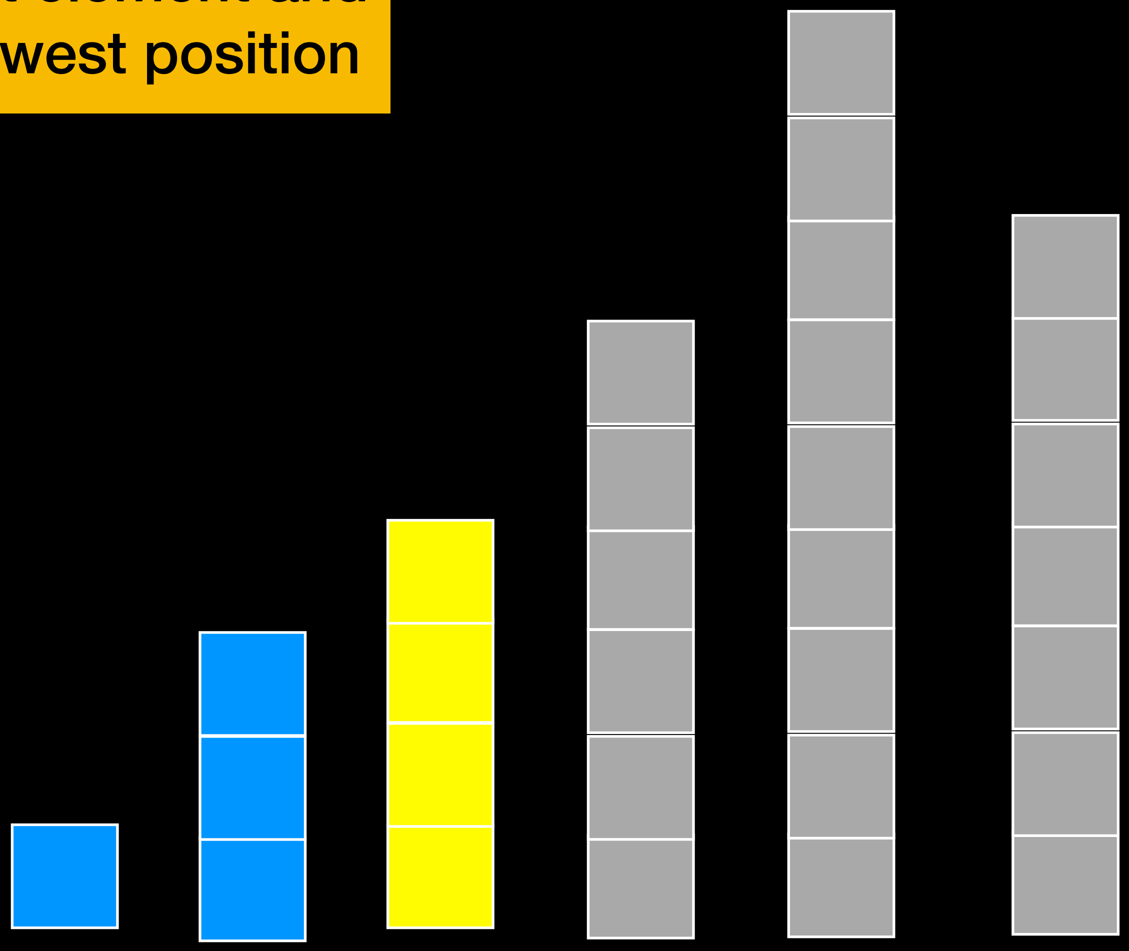


Selection Sort



Find smallest element and move it at lowest position

3rd Pass



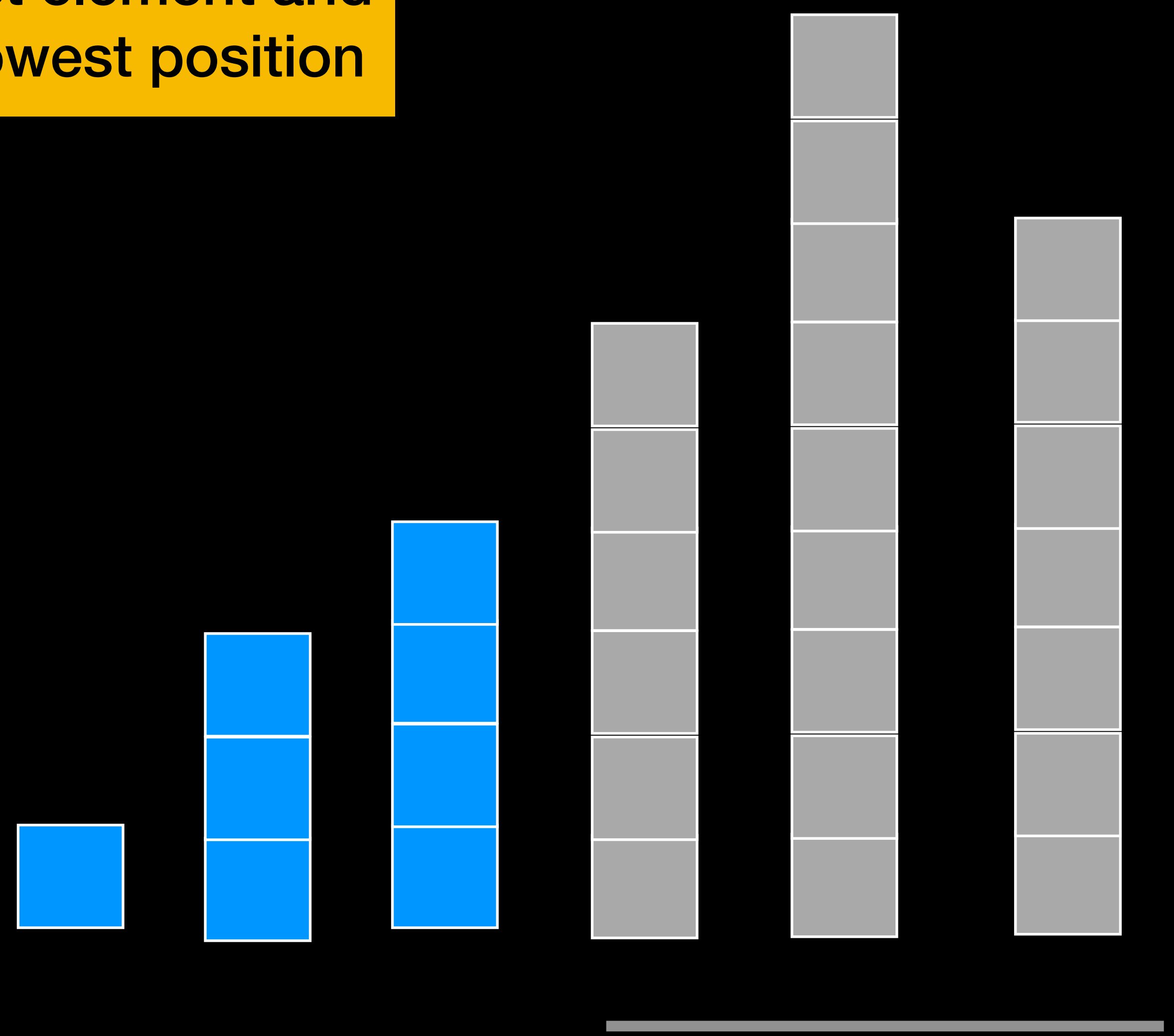
Selection Sort

Unsorted

Sorted

Find smallest element and move it at lowest position

4th Pass



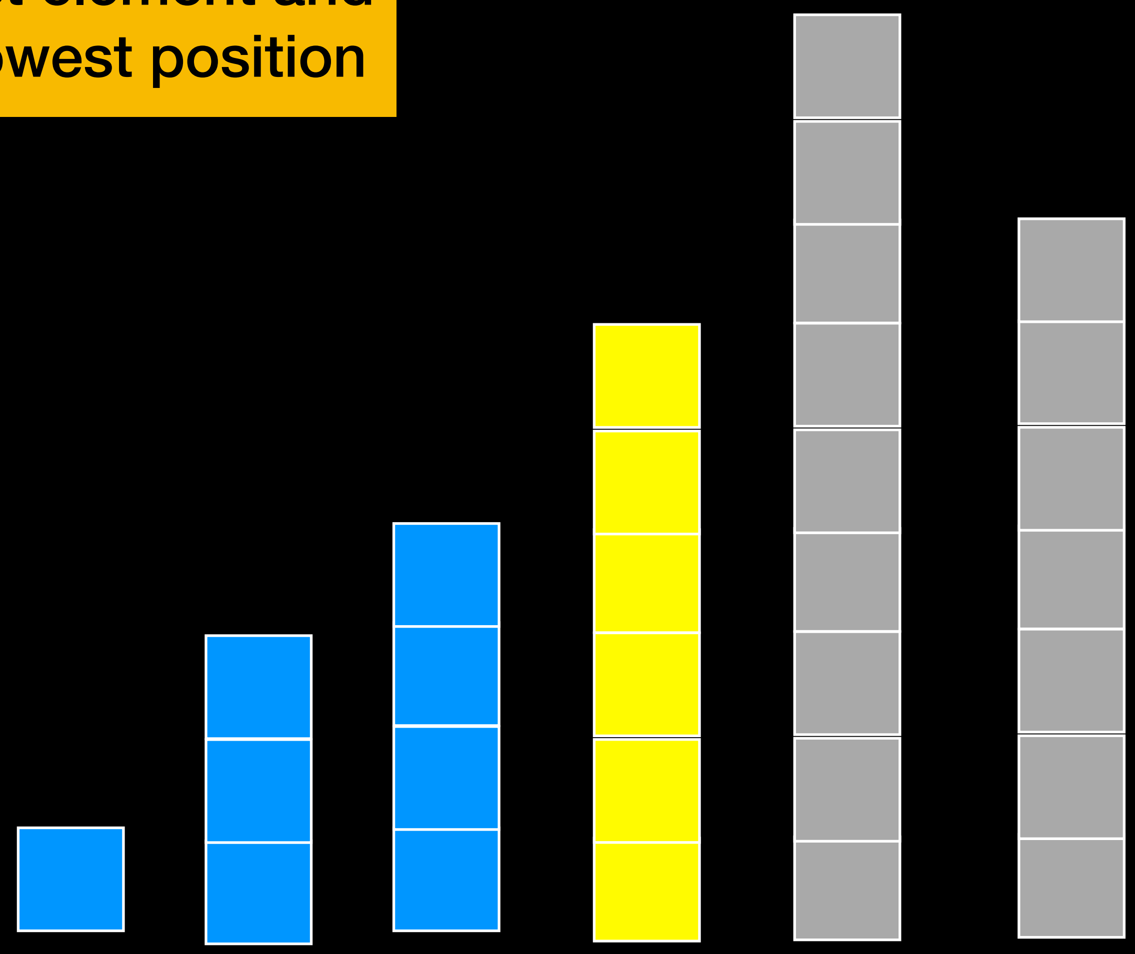
Selection Sort

Unsorted

Sorted

Find smallest element and move it at lowest position

4th Pass



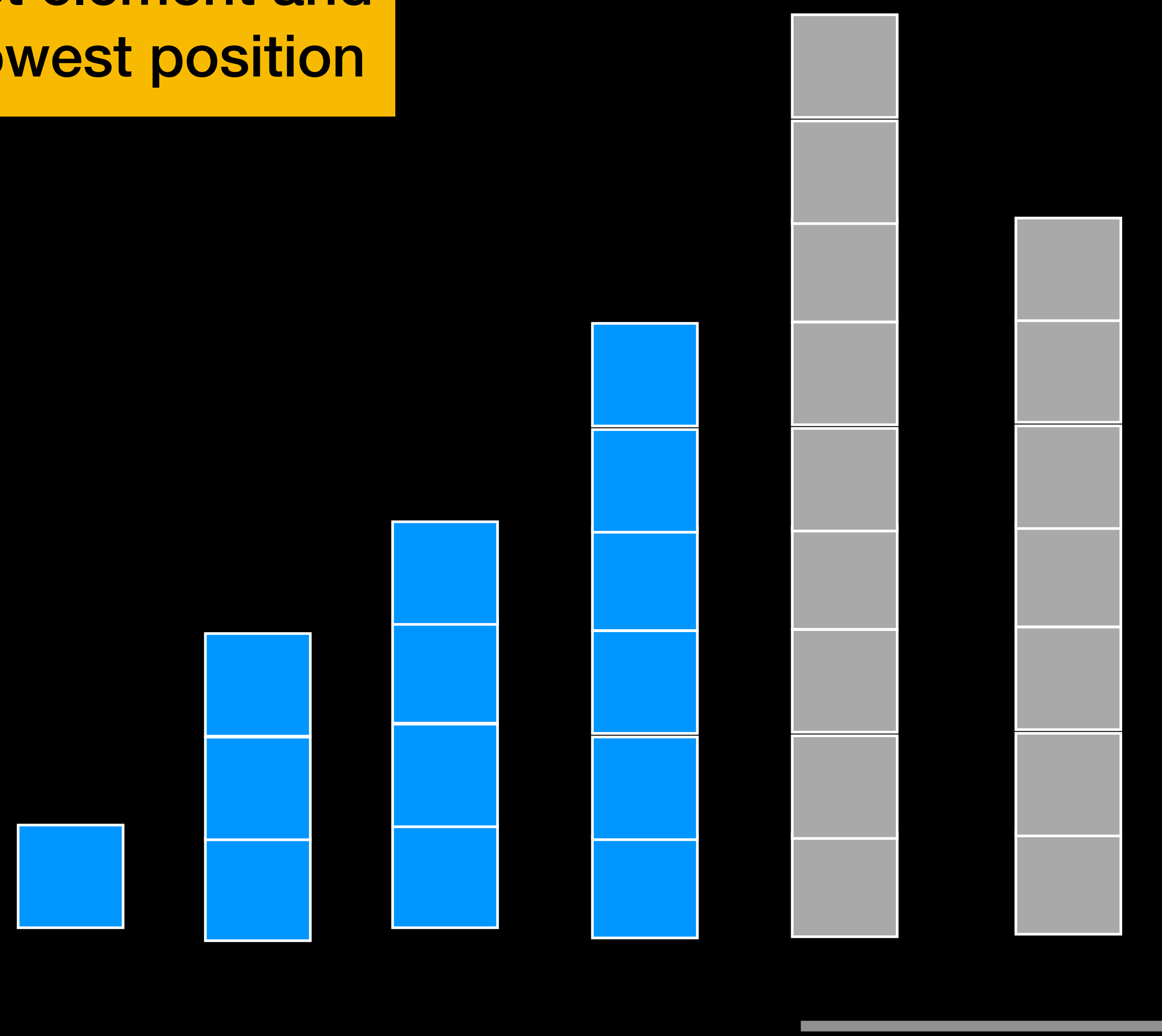
Selection Sort

Unsorted

Sorted

Find smallest element and move it at lowest position

5th Pass



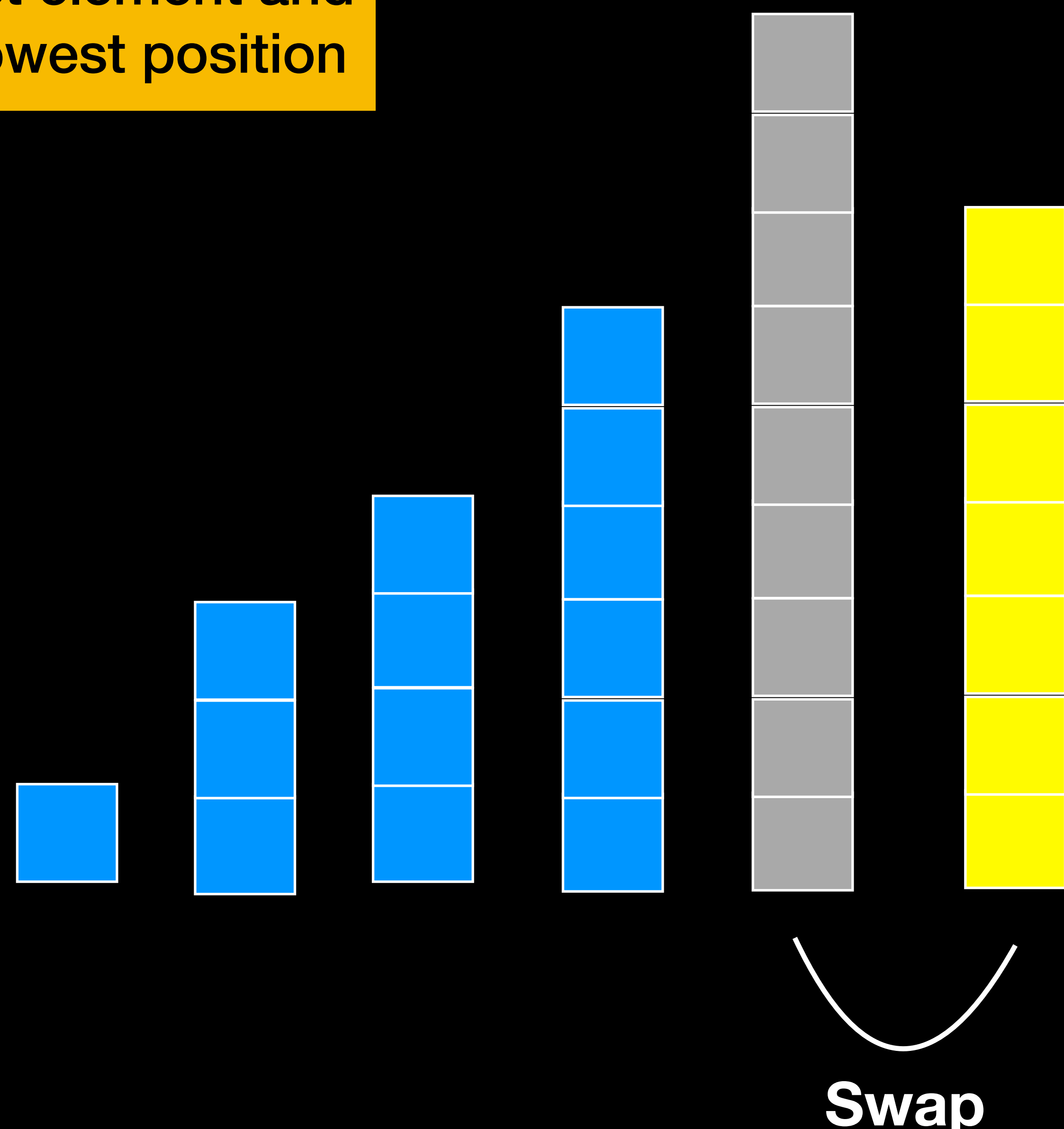
Selection Sort

Find smallest element and move it at lowest position

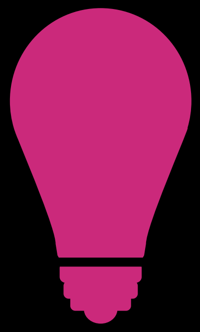
Unsorted

Sorted

5th Pass



Selection Sort



Unsorted

Sorted

Find smallest element and move it at lowest position

5th Pass

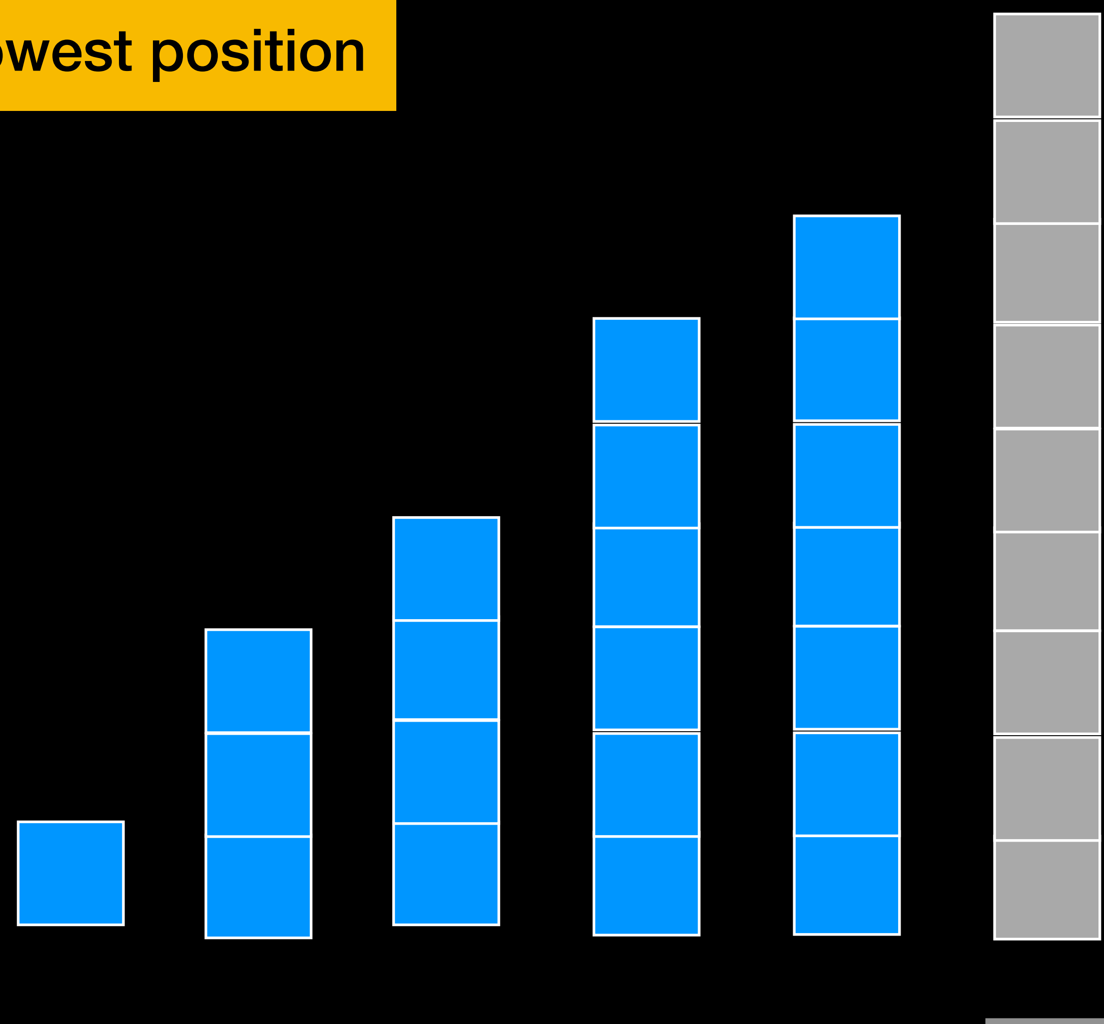
Selection Sort

Unsorted

Sorted

Find smallest element and move it at lowest position

6th Pass

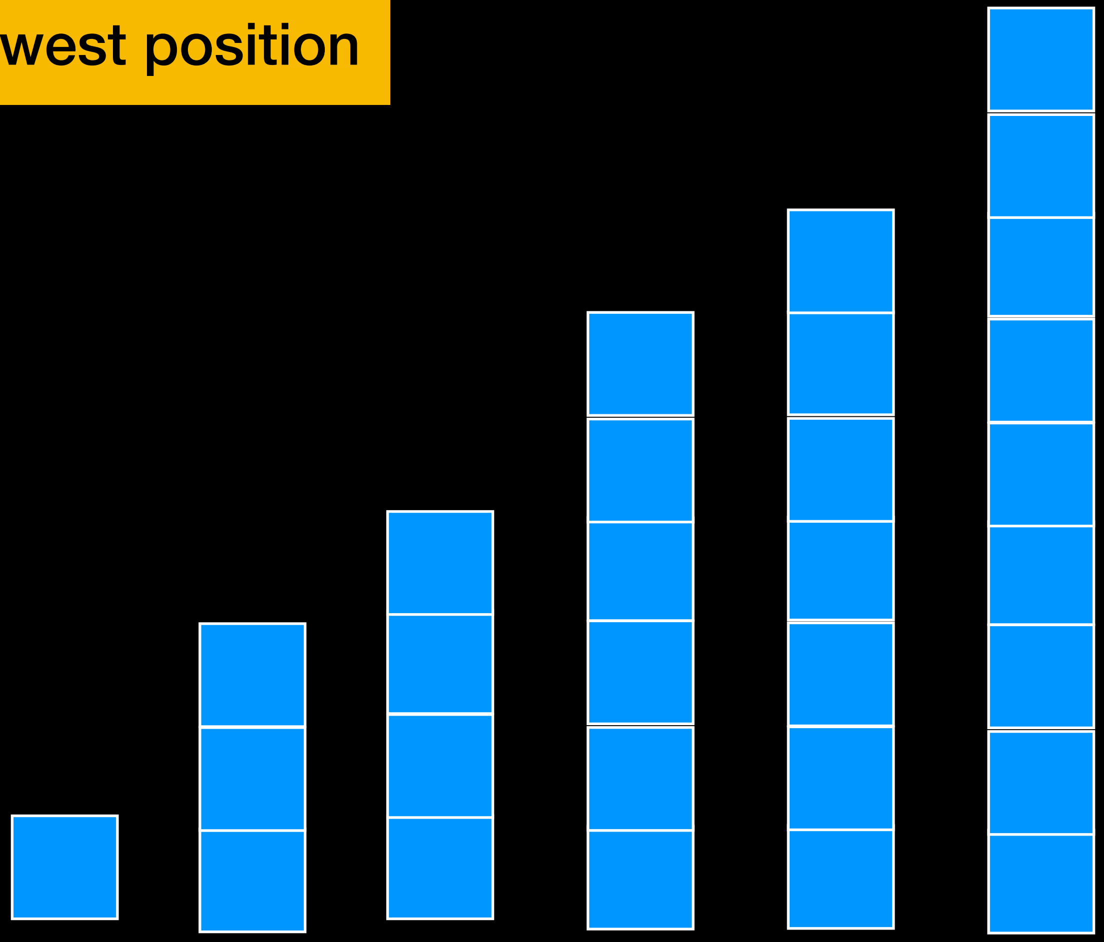


Selection Sort

Unsorted

Sorted

Find smallest element and move it at lowest position



Selection Sort

Find the smallest item and move it at position 1

Find the next-smallest item and move it at position 2

. . .

Selection Sort Analysis

How much work?

Find smallest: look at **n** elements

Selection Sort Analysis

How much work?

Find smallest: look at **n** elements

Find second smallest: look at **n-1** elements

Selection Sort Analysis

How much work?

Find smallest: look at **n** elements

Find second smallest: look at **n-1** elements

Find third smallest: look at **n-2** elements

. . .

Selection Sort Analysis

How much work?

Find smallest: look at **n** elements

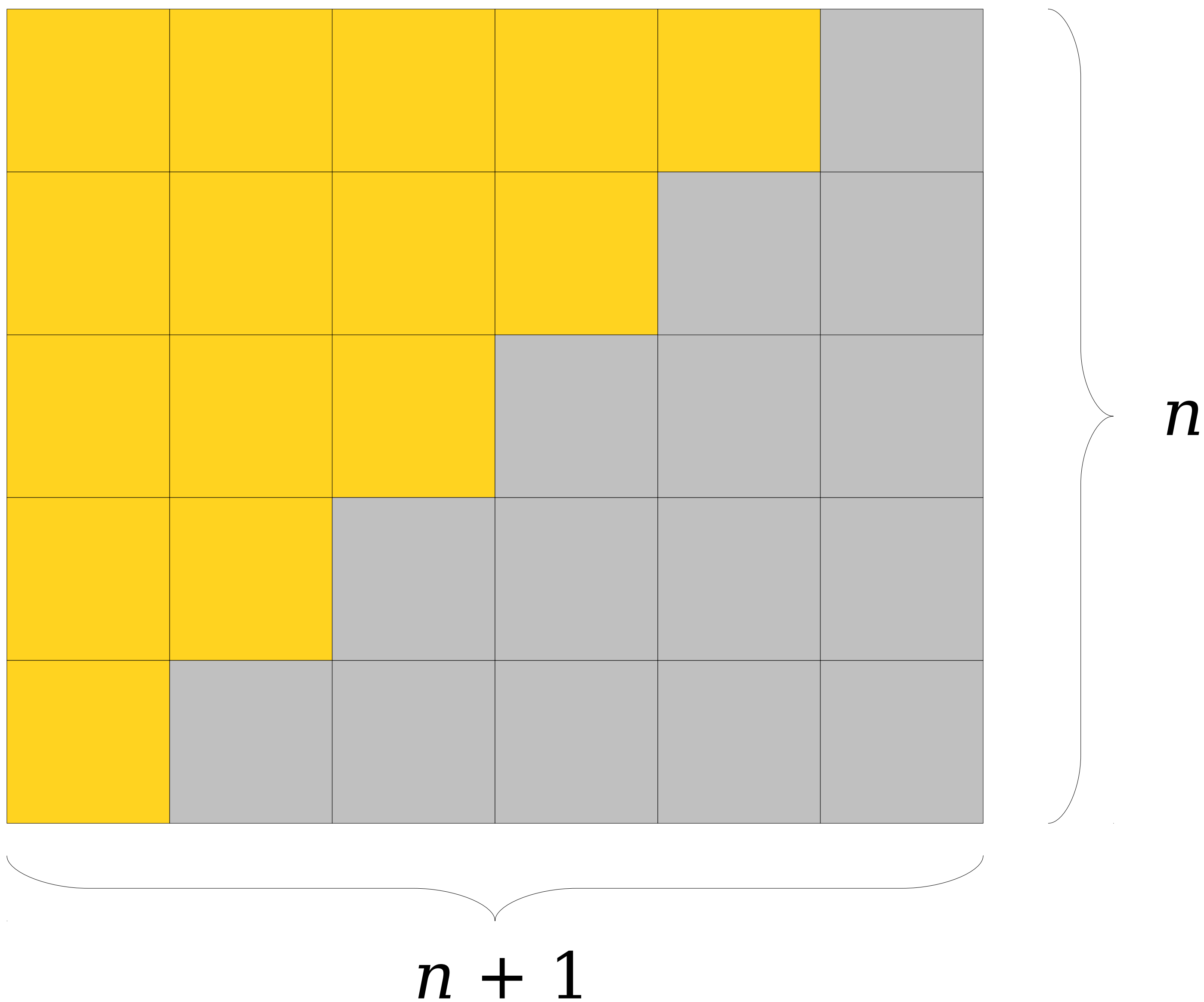
Find second smallest: look at **n-1** elements

Find third smallest: look at **n-2** elements

. . .

Total work: **n + (n-1) + (n-2) + . . . +1**

$$n + (n\text{-}1) + \ldots + 2 + 1 = n(n+1) / 2$$



Derivation

1 + 2 + 3 + … + (n-2) + (n-1) + n

n + (n-1) + (n-2) + … + 3 + 2 +1

Now add the two series together term by term.

(n+1) + (n-1+2) + (n-2+3) + … + (3+n-2) + (2+n-1) + (1+n)

= (n+1) + (n+1) + (n+1) + … + (n+1) + (n +1) + (n+1)

You have added (n+1) a total of n times, so the sum is n(n+1).

You added the series twice, so adding the series once will give you n(n+1)/2

Selection Sort Analysis

$T(n) = n(n+1) / 2$ comparisons $+ n$ data moves $= O(\ )$?

Selection Sort Analysis

$T(n) = n(n+1) / 2$ comparisons $+ n$ data moves $= O(\ )$?

$T(n) = (n^2+n) / 2 + n = O(\ )$?

Selection Sort Analysis

$T(n) = n(n+1) / 2$ comparisons + n data moves = $O(\ )$?

$T(n) = (n^2+n) / 2 + n = O(\ )$?

Ignore constant

Ignore non-dominant terms

Selection Sort Analysis

$T(n) = n(n+1) / 2$ comparisons $+ n$ data moves $= O(\ )$?

$T(n) = (n^2+n) / 2 + n = O(\mathbf{n^2})$

Ignore constant

Ignore non-dominant terms

Selection Sort Analysis

$T(n) = n(n+1) / 2$ comparisons + n data moves = $O(\ )$?

$T(n) = (n^2+n) / 2 + n = O(n^2)$

Selection Sort run time is **$O(n^2)$**

```cpp
template <class Comparable>
void selectionSort(const std::vector<Comparable>& the_array)
{
   int size = the_array.size();
   // first = index of the first item in the subarray of items yet
   //        to be sorted;
   // smallest = index of the smallest item found
   for (int first = 0; first < size; first++)
   {
      // At this point, the_array[0 ...first-1] is sorted, and its
      // entries are <= those in the_array[first ... size-1].
      // Select the smallest entry in the_array[first ... size-1]
      int smallest_index = findIndexOfSmallest(the_array, first, size);

      // Swap the smallest entry, the_array[smallest_index], with
      // the first in the unsorted subarray the_array[first]
      std::swap(the_array[smallest_index], the_array[first]);
   }  // end for
}  // end selectionSort
```

```
template <class Comparable>
void selectionSort(const std::vector<Comparable>& the_array)
{
   int size = the_array.size();
   // first = index of the first item in the subarray of items yet
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      // the first in the unsorted subarray the_array[first]
      std::swap(the_array[smallest_index], the_array[first]);
   }  // end for
}  // end selectionSort
```

Pass O(n)

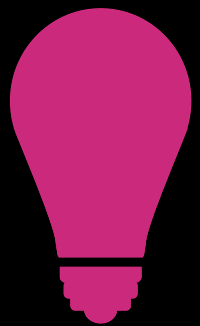
O(n)

$O(n^2)$

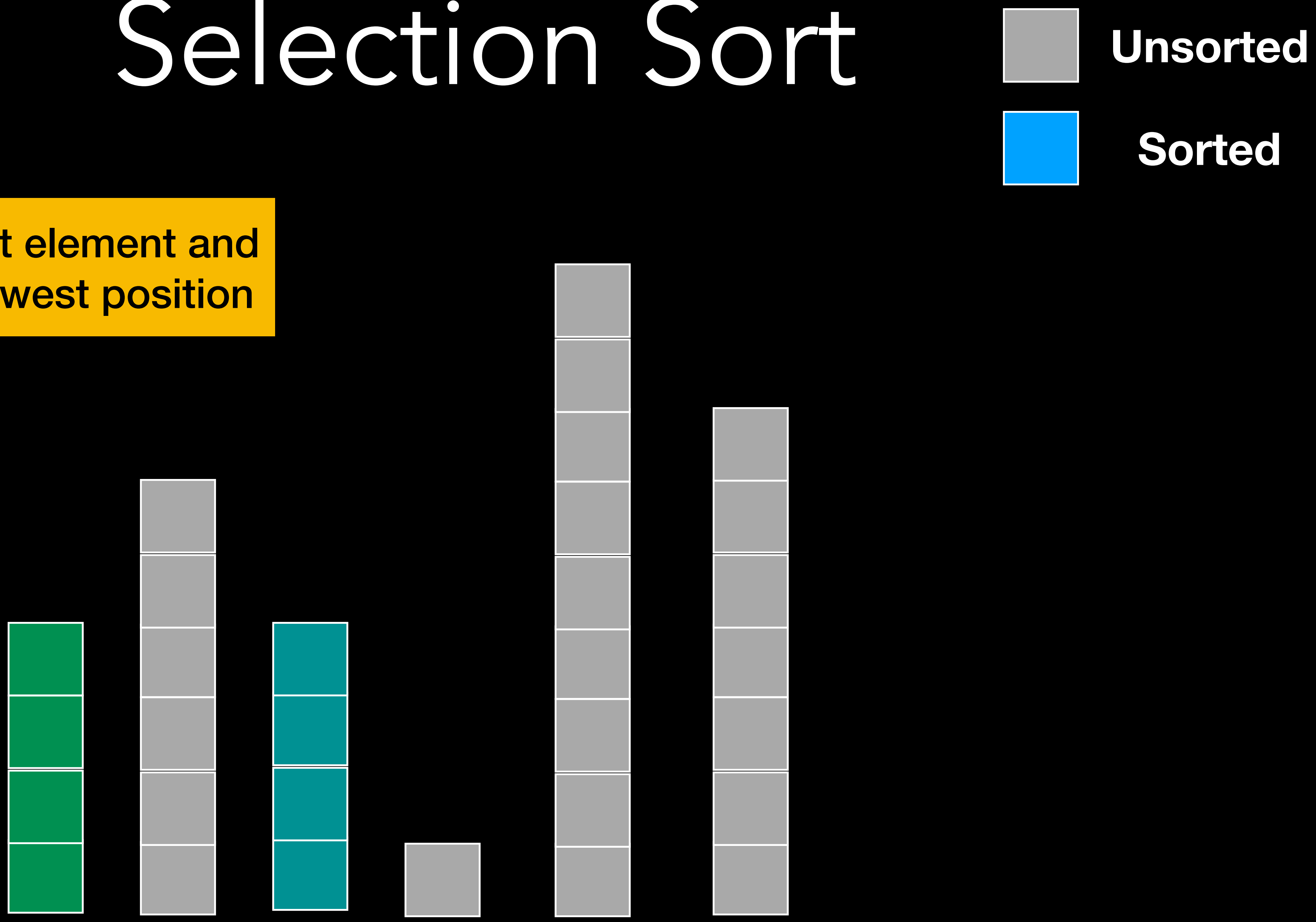
Stability

A sorting algorithm is Stable if elements that are equal remain in same order relative to each other after sorting

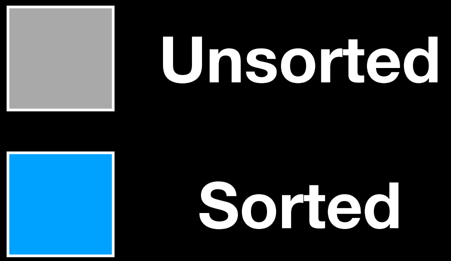
Selection Sort

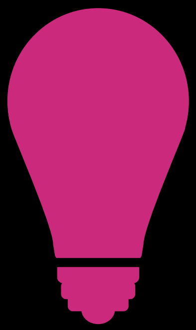


Find smallest element and move it at lowest position



Selection Sort





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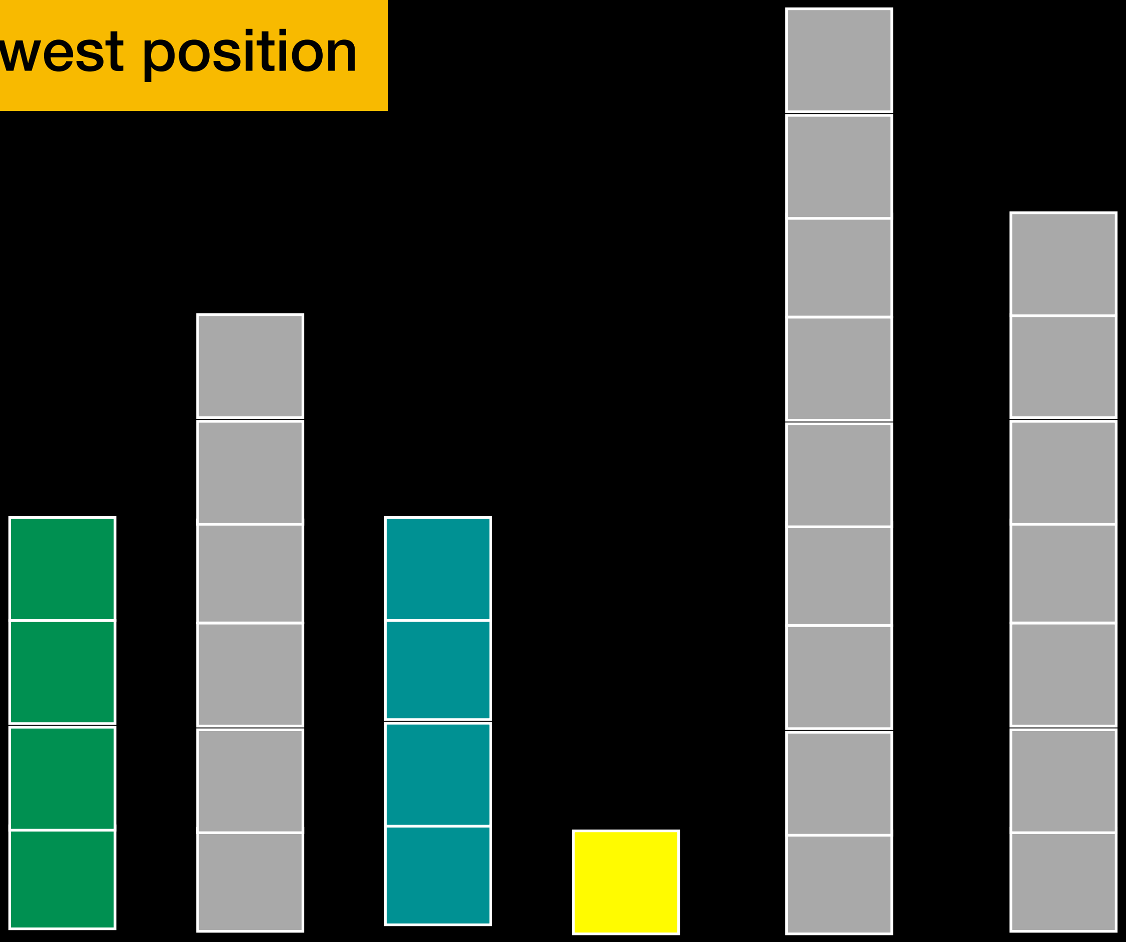


Selection Sort

Unsorted

Sorted

Find smallest element and move it at lowest position

Selection Sort

Find smallest element and move it at lowest position

Selection Sort Analysis

Execution time DOES NOT depend on initial arrangement of data => ALWAYS $O(n^2)$

$O(n^2)$ comparisons

Good choice for small **n** and/or data moves are costly ($O(n)$ data moves)

Unstable

Understanding $O(n^2)$

100	14	3	43	200	274

$T(n)$

Understanding O(n^2)

100	14	3	43	200	274

$T(n)$

100	14	3	43	200	274	523	108	76	195	599	158

$T(2n) \approx 4T(n)$

Double data = Quadruple time

$(2n)^2 = 4n^2$

Understanding O(n^2)

100	14	3	43	200	274

$T(n)$

100	14	3	43	200	274	523	108	76	195	599	158	2	260	11	64	932	5

$T(3n) \approx 9T(n)$

Triple data = Nonuple time

$(3n)^2 = 9n^2$

Understanding $O(n^2)$ on large input

If size of input increases by factor of 100

Execution time increases by factor of 10,000

$T(100n) = 10{,}000T(n)$

Understanding $O(n^2)$ on large input

If size of input increases by factor of 100

Execution time increases by factor of 10,000

$T(100n) = 10{,}000T(n)$

Assume $n = 100{,}000$ and $T(n) = 17$ seconds

Sorting 10,000,000 takes 10,000 longer

Understanding $O(n^2)$ on large input

If size of input increases by factor of 100

Execution time increases by factor of 10,000

$T(100n) = 10{,}000T(n)$

Assume $n = 100{,}000$ and $T(n) = 17$ seconds

Sorting 10,000,000 takes 10,000 longer

Sorting 10,000,000 entries takes ≈ 2 days

Multiplying input by 100 to go from 17sec to 2 days!!!

Raise your hand if you had Selection Sort

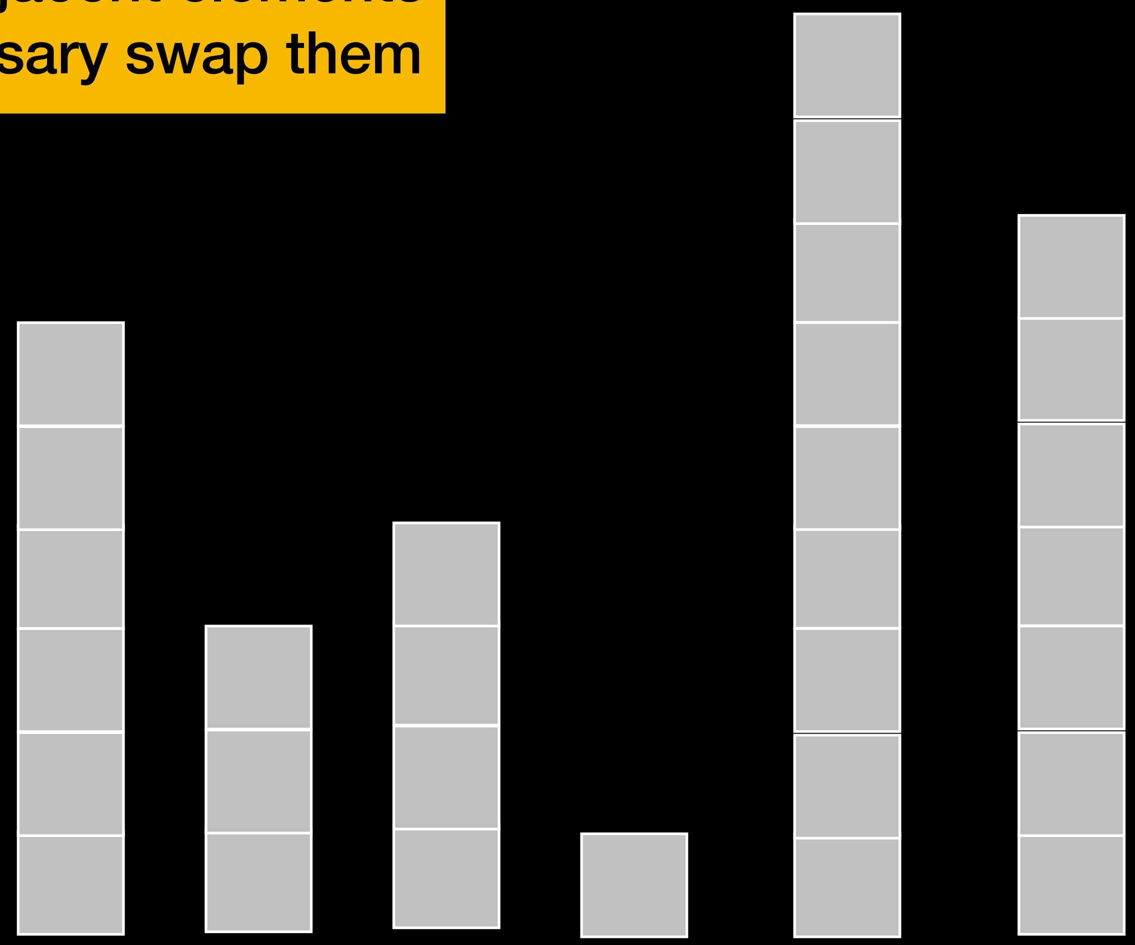
Bubble Sort

Bubble Sort

Unsorted

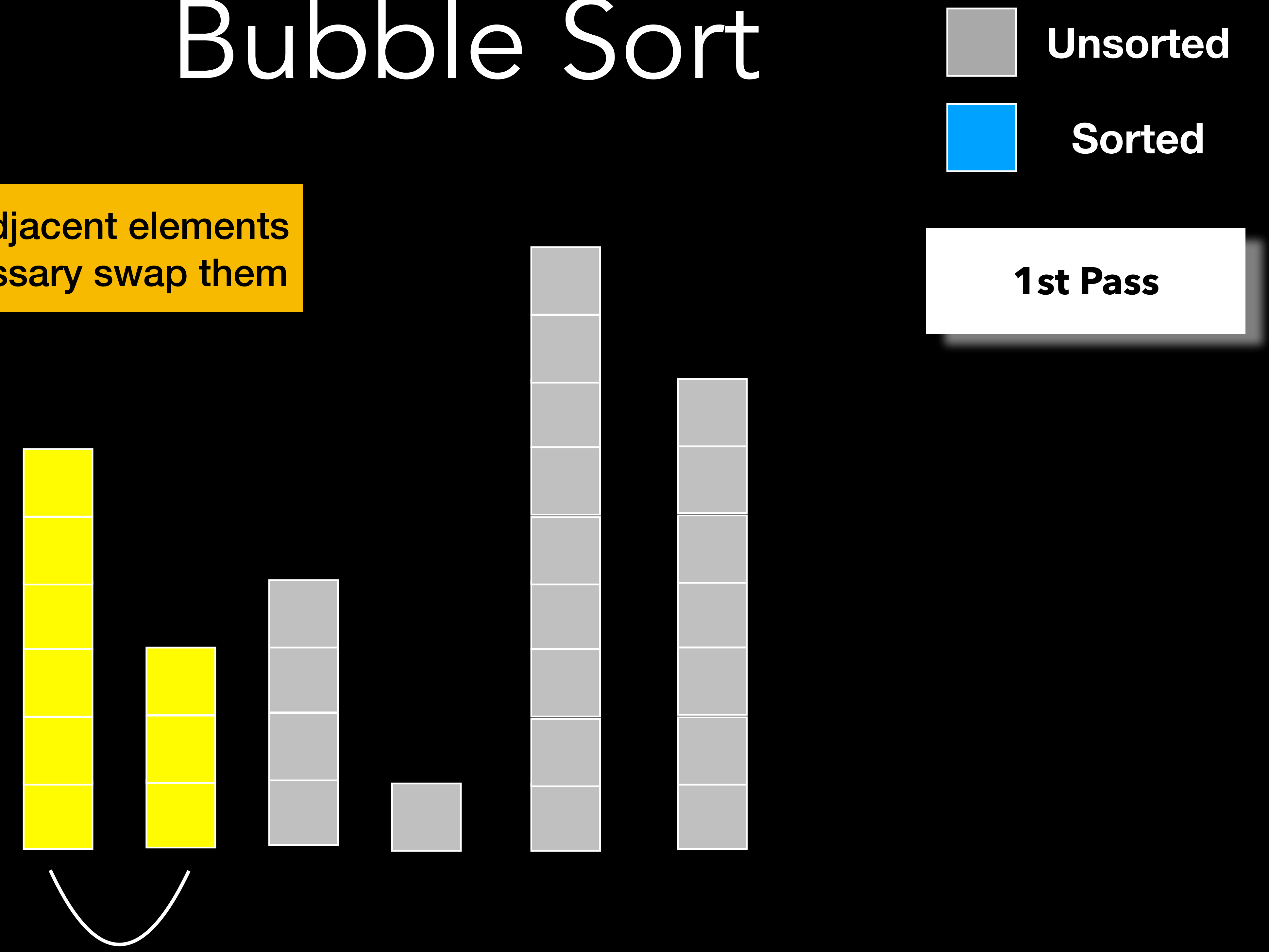
Sorted

Compare adjacent elements and if necessary swap them

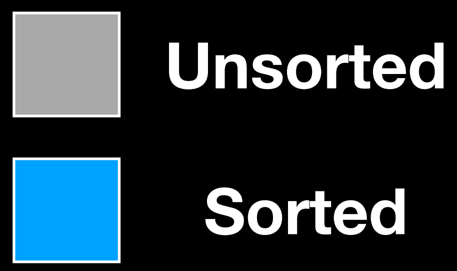


Bubble Sort

Compare adjacent elements and if necessary swap them

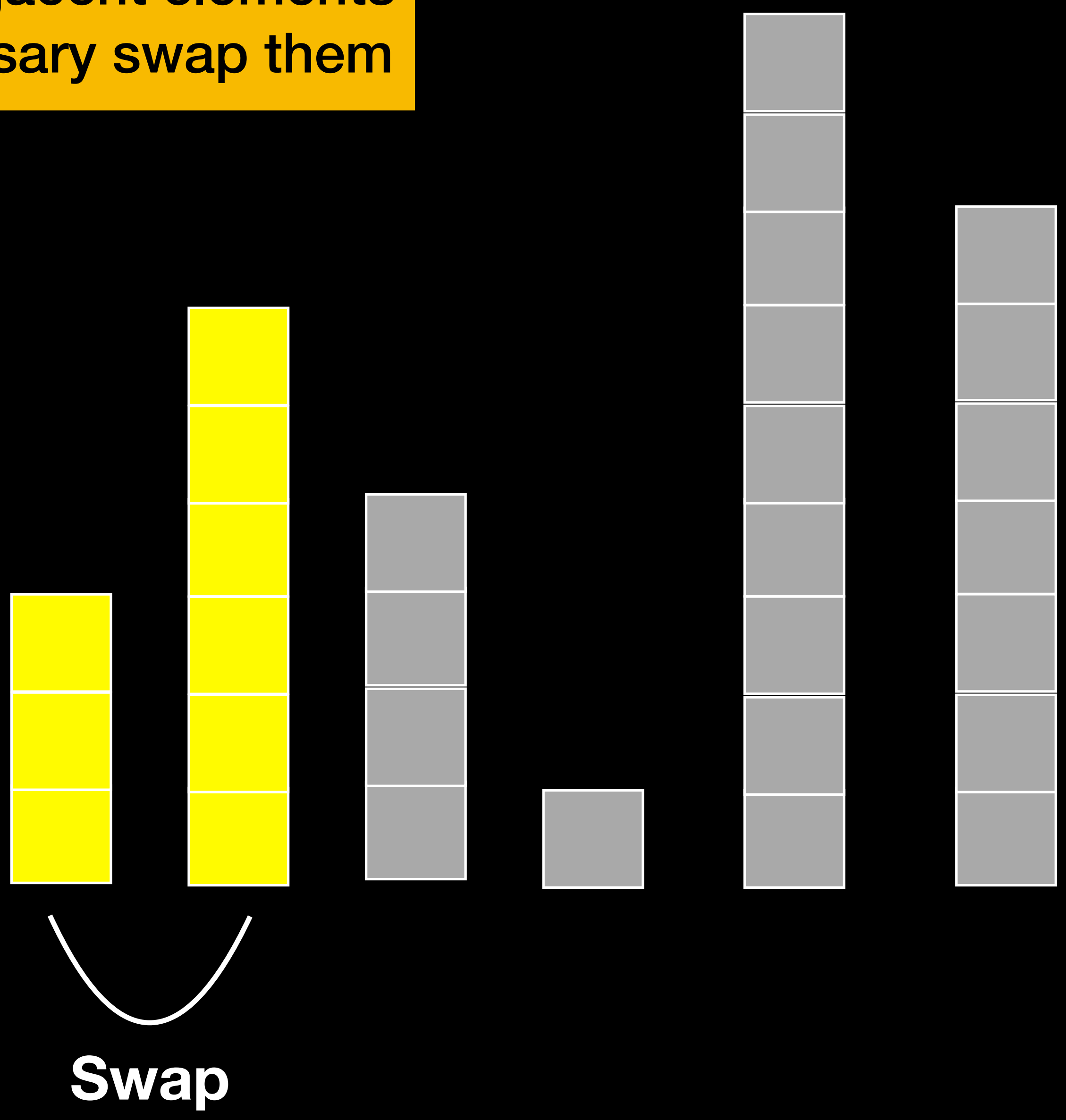


Bubble Sort



Compare adjacent elements and if necessary swap them

1st Pass



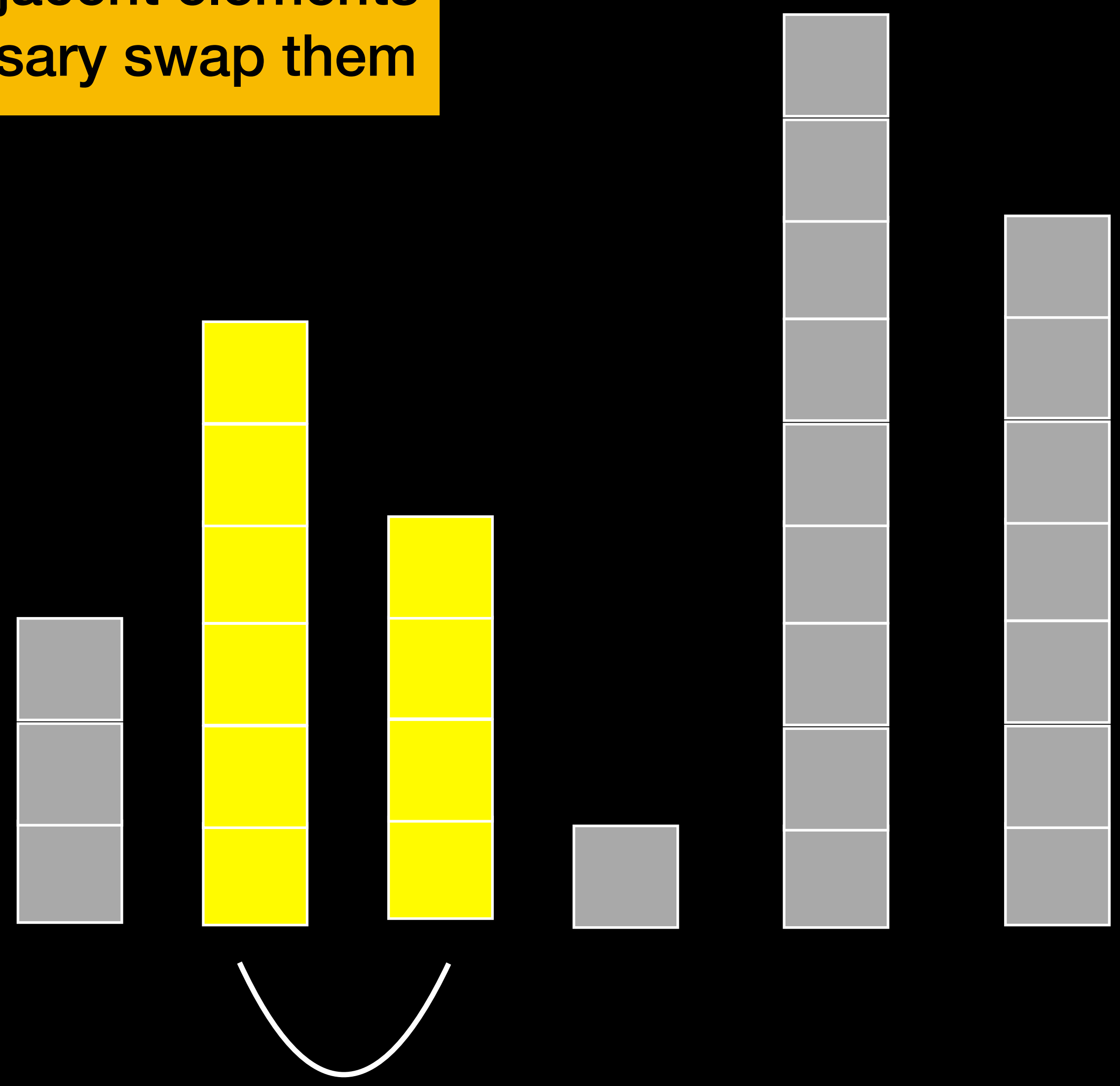
Bubble Sort

Unsorted

Sorted

Compare adjacent elements and if necessary swap them

1st Pass



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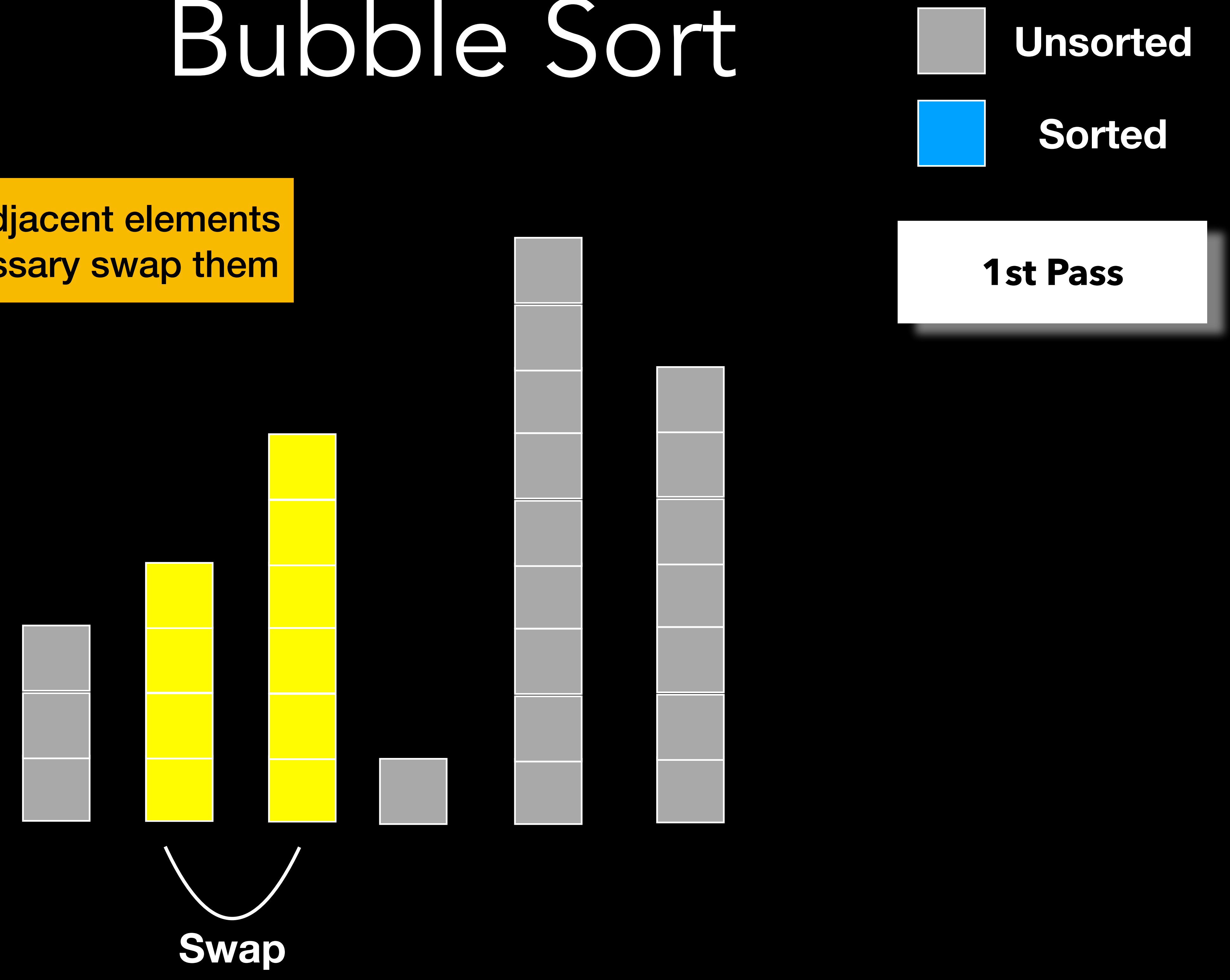


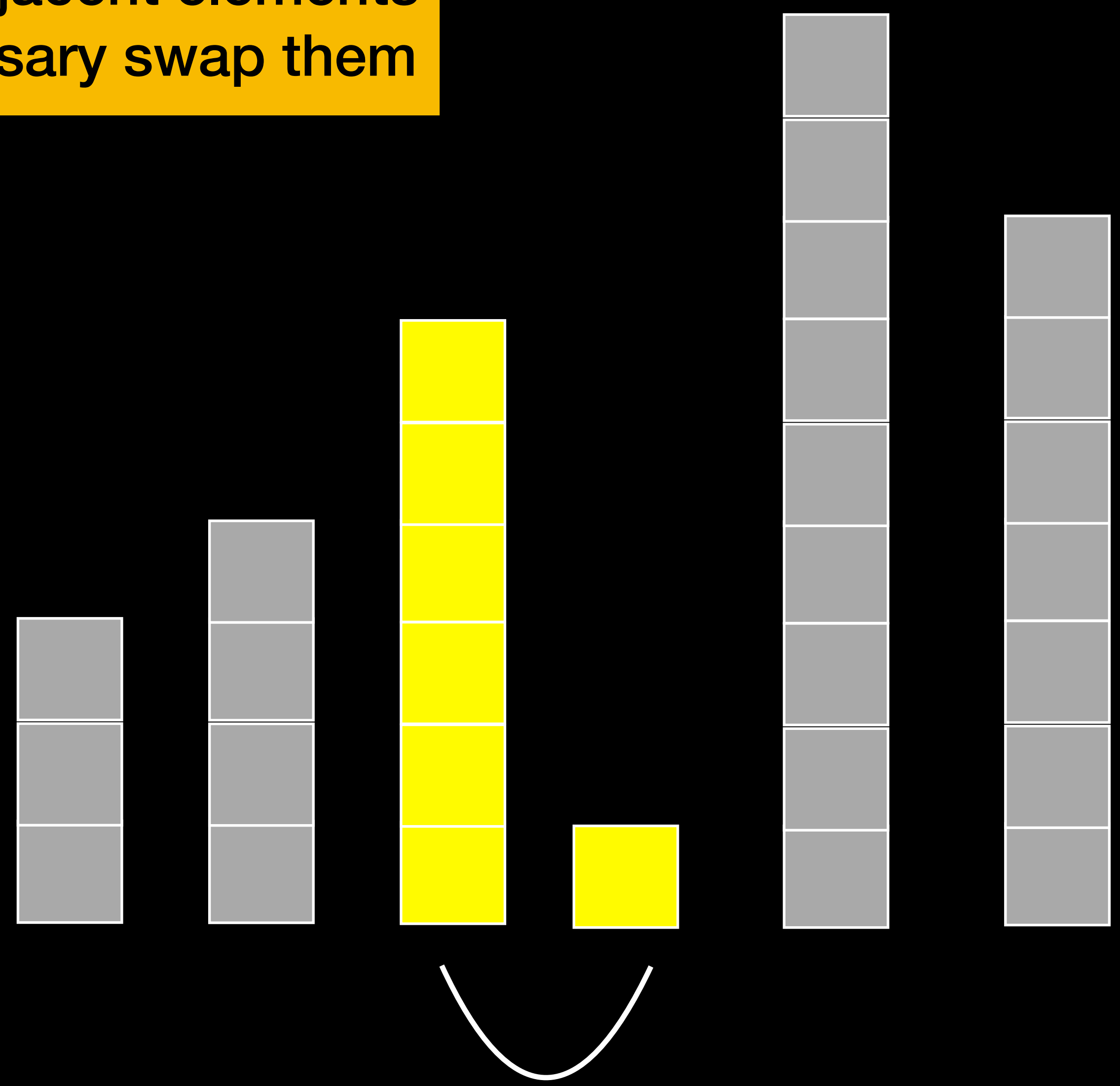
Bubble Sort

Unsorted

Sorted

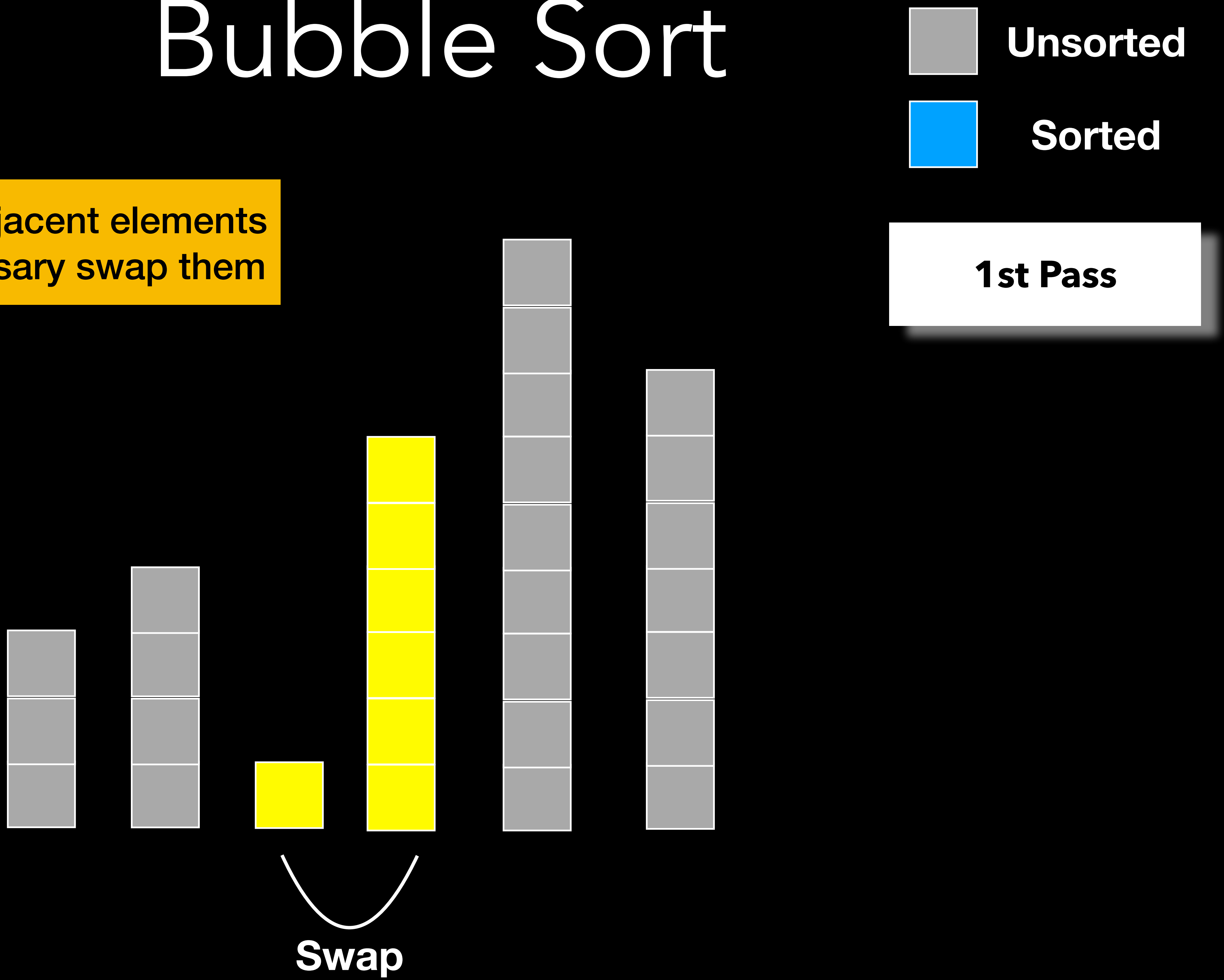
Compare adjacent elements and if necessary swap them

1st Pass



Bubble Sort

Compare adjacent elements and if necessary swap them



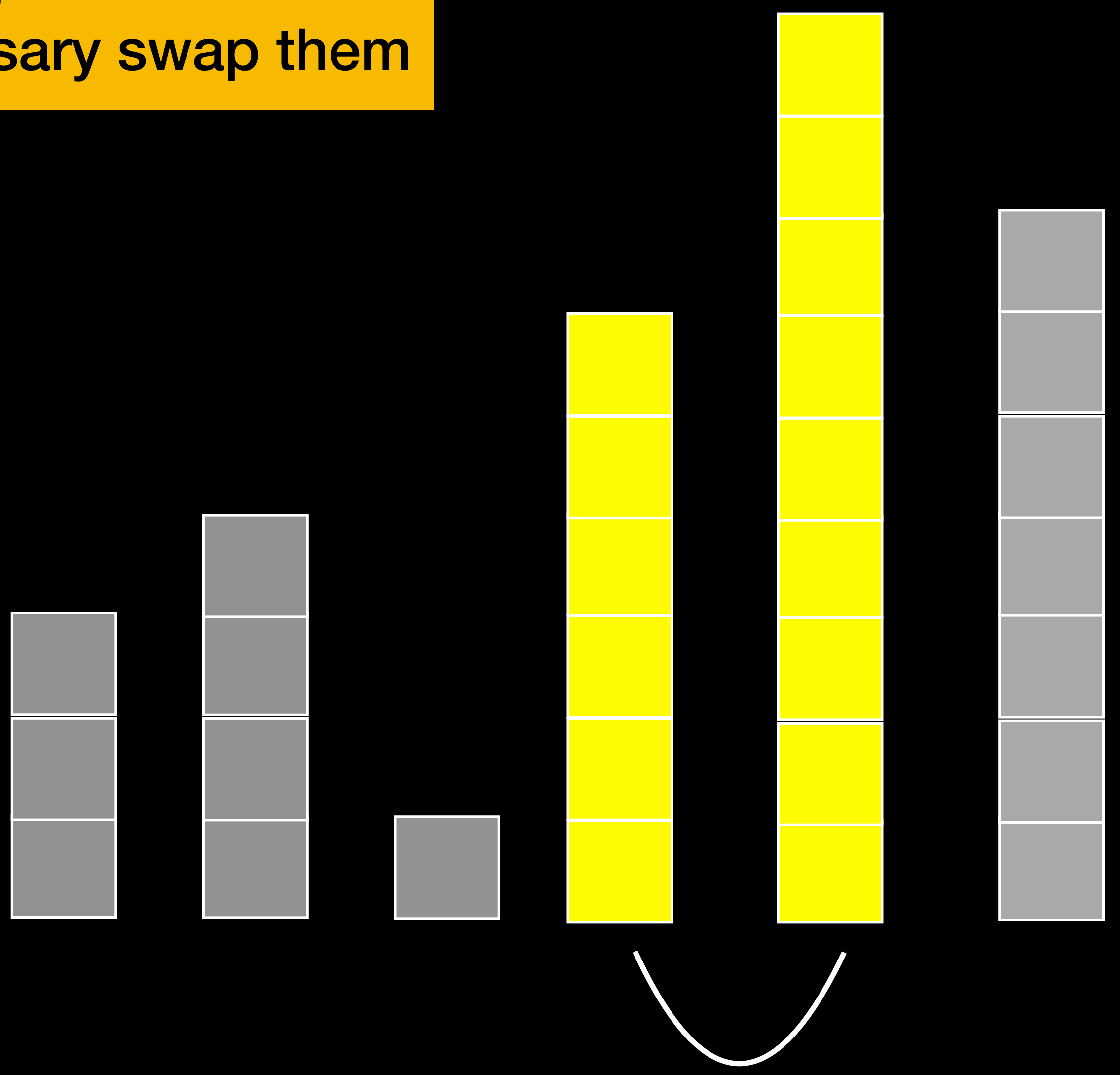
Bubble Sort

Unsorted

Sorted

1st Pass

Compare adjacent elements and if necessary swap them



Bubble Sort

Unsorted

Sorted

1st Pass

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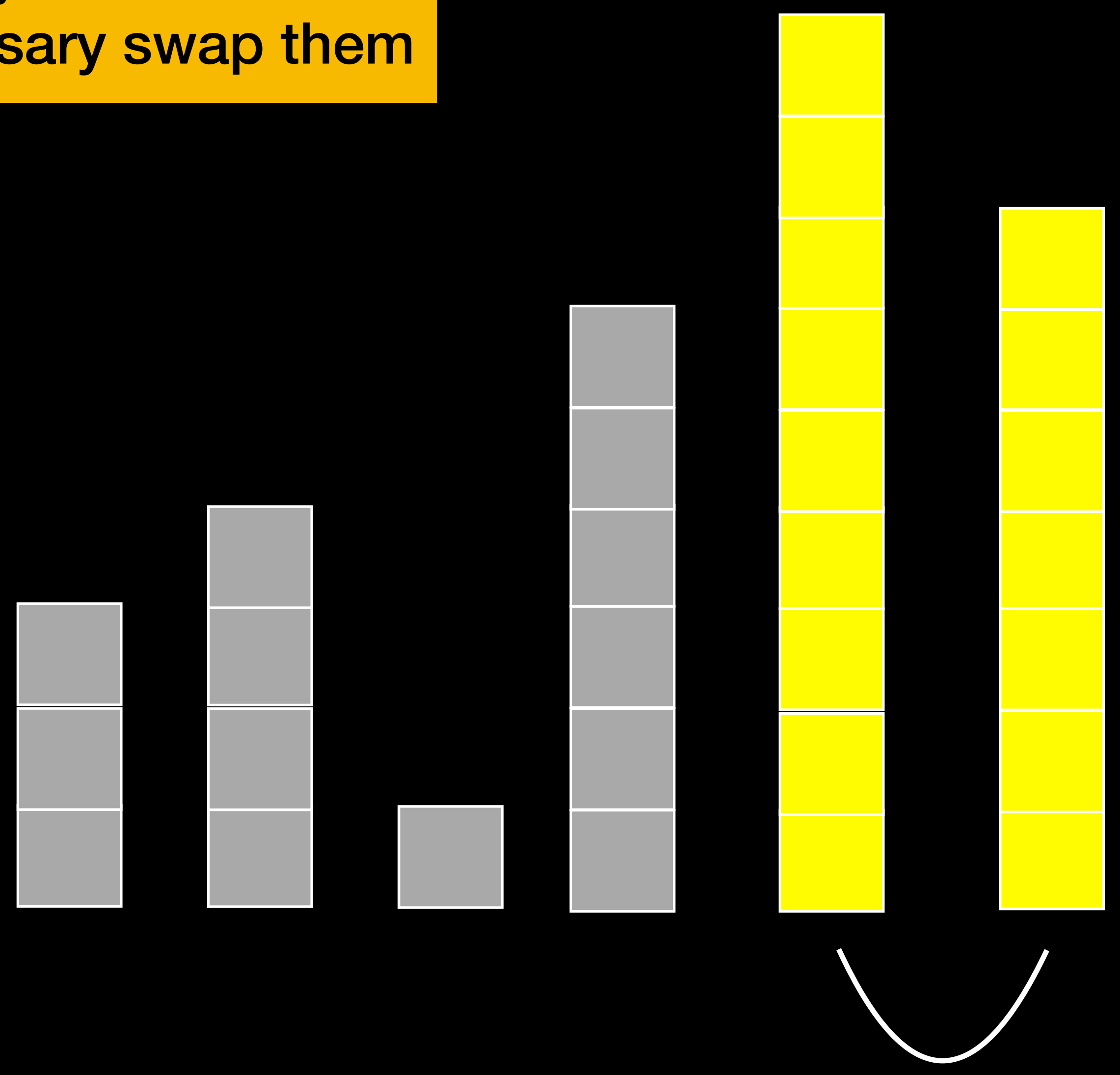
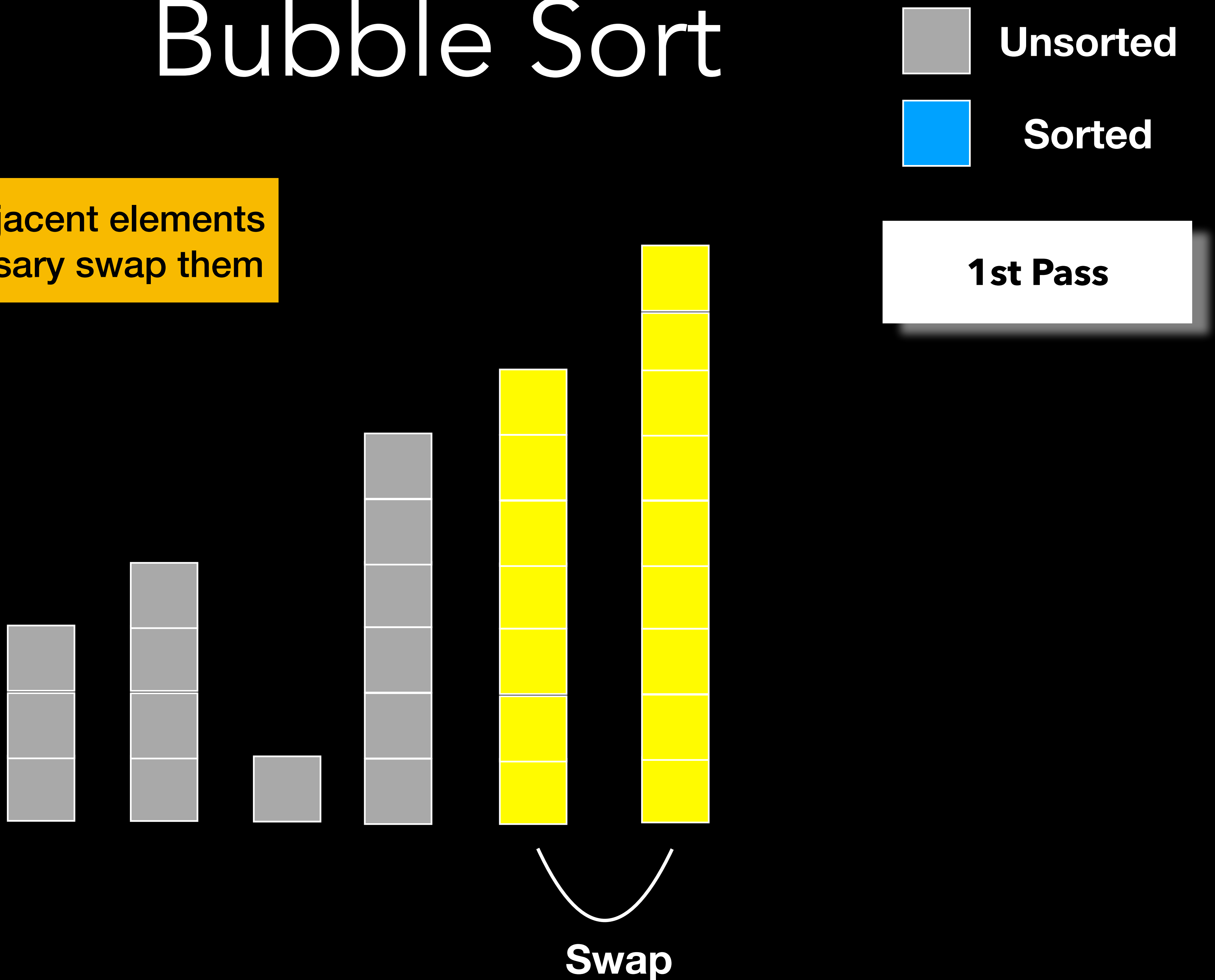


Bubble Sort

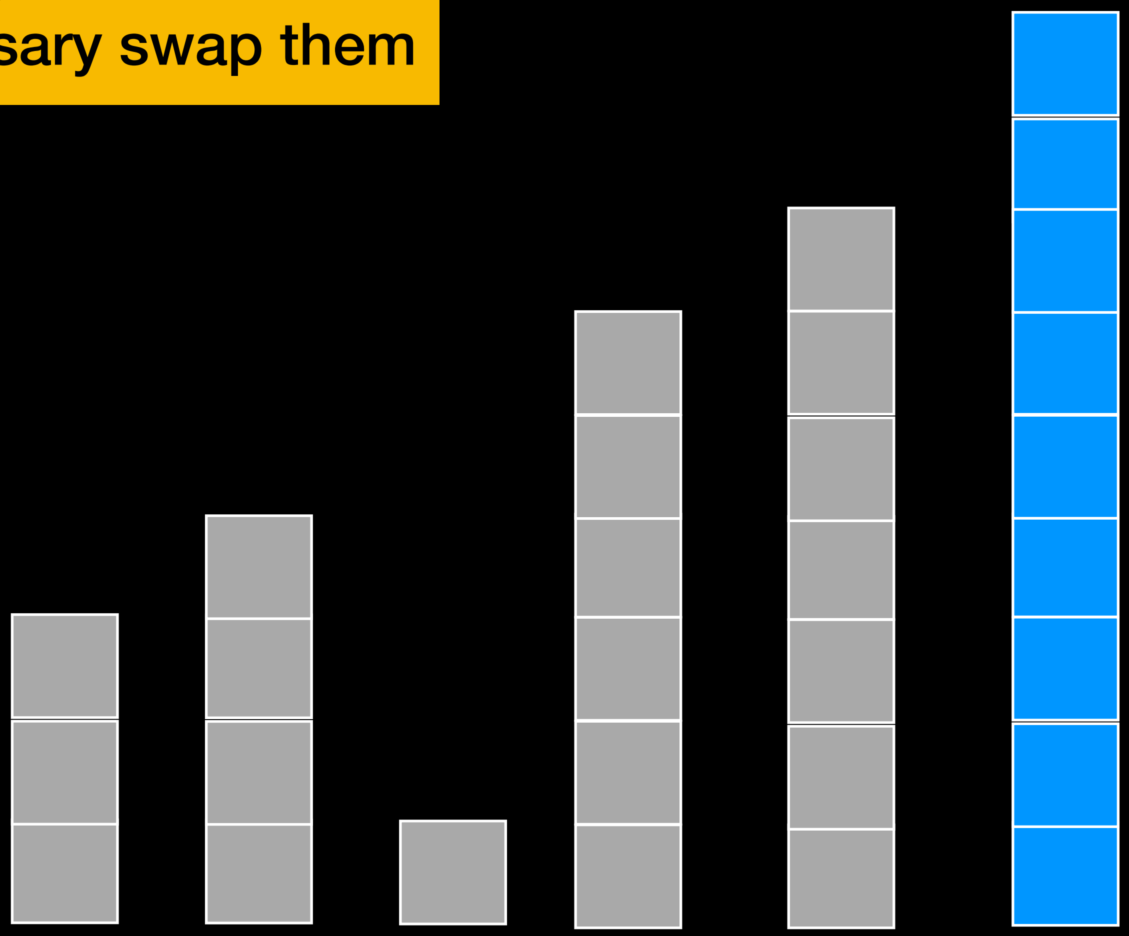
Compare adjacent elements and if necessary swap them



Bubble Sort

Compare adjacent elements and if necessary swap them

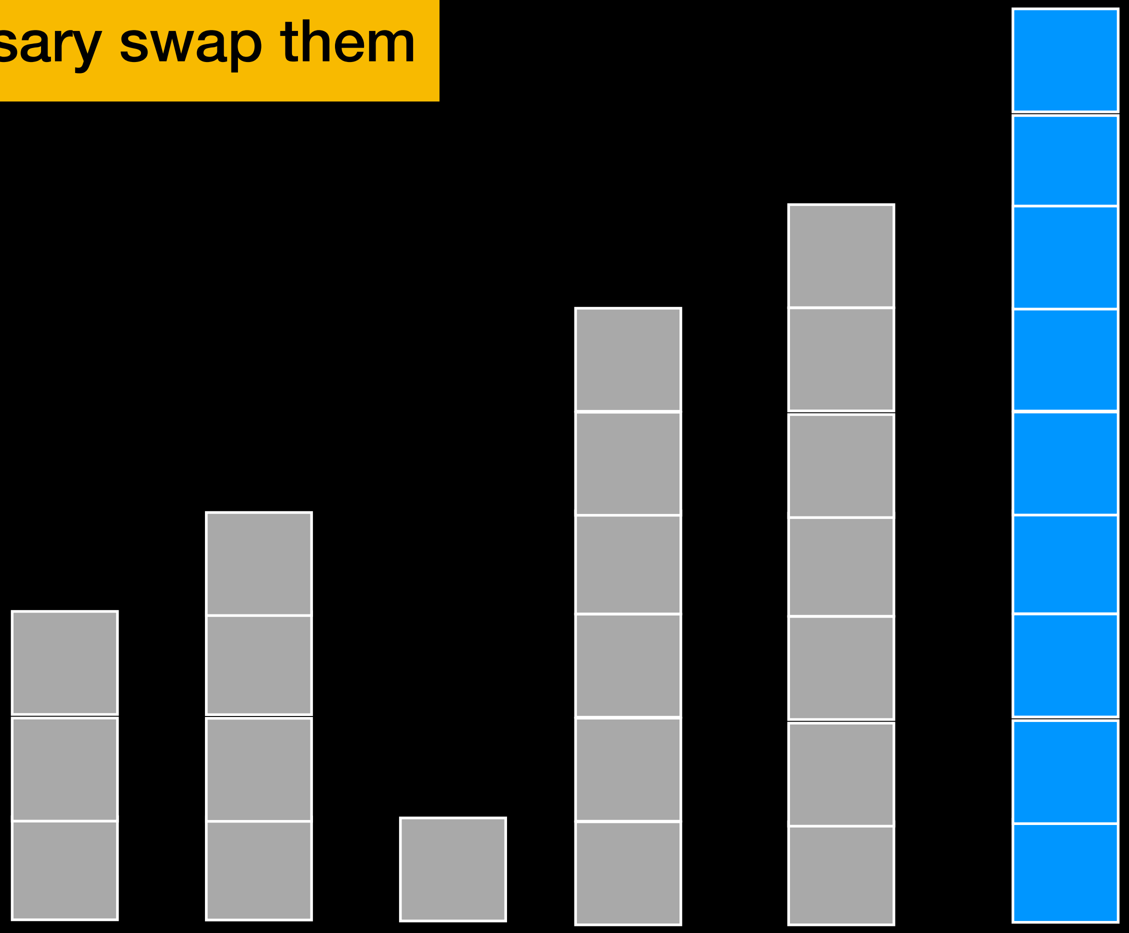
End of1st Pass:
Not sorted, but largest has ***"bubbled up"*** to its proper position



Bubble Sort

Compare adjacent elements and if necessary swap them

2nd Pass:
Sort **n-1**



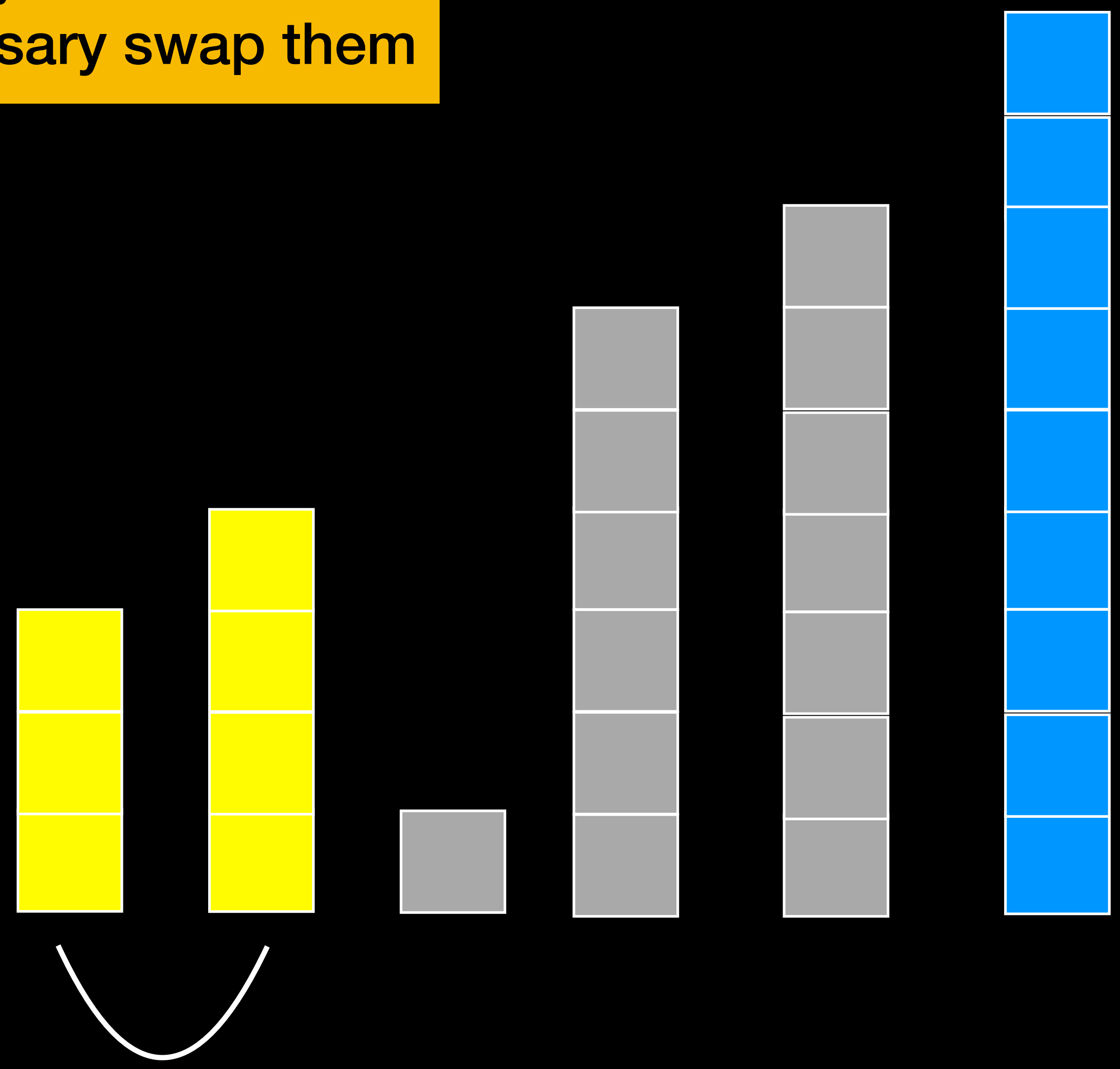
Bubble Sort

Unsorted

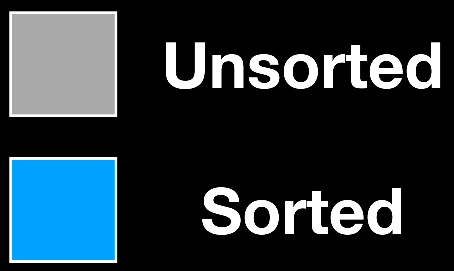
Sorted

Compare adjacent elements and if necessary swap them

2nd Pass

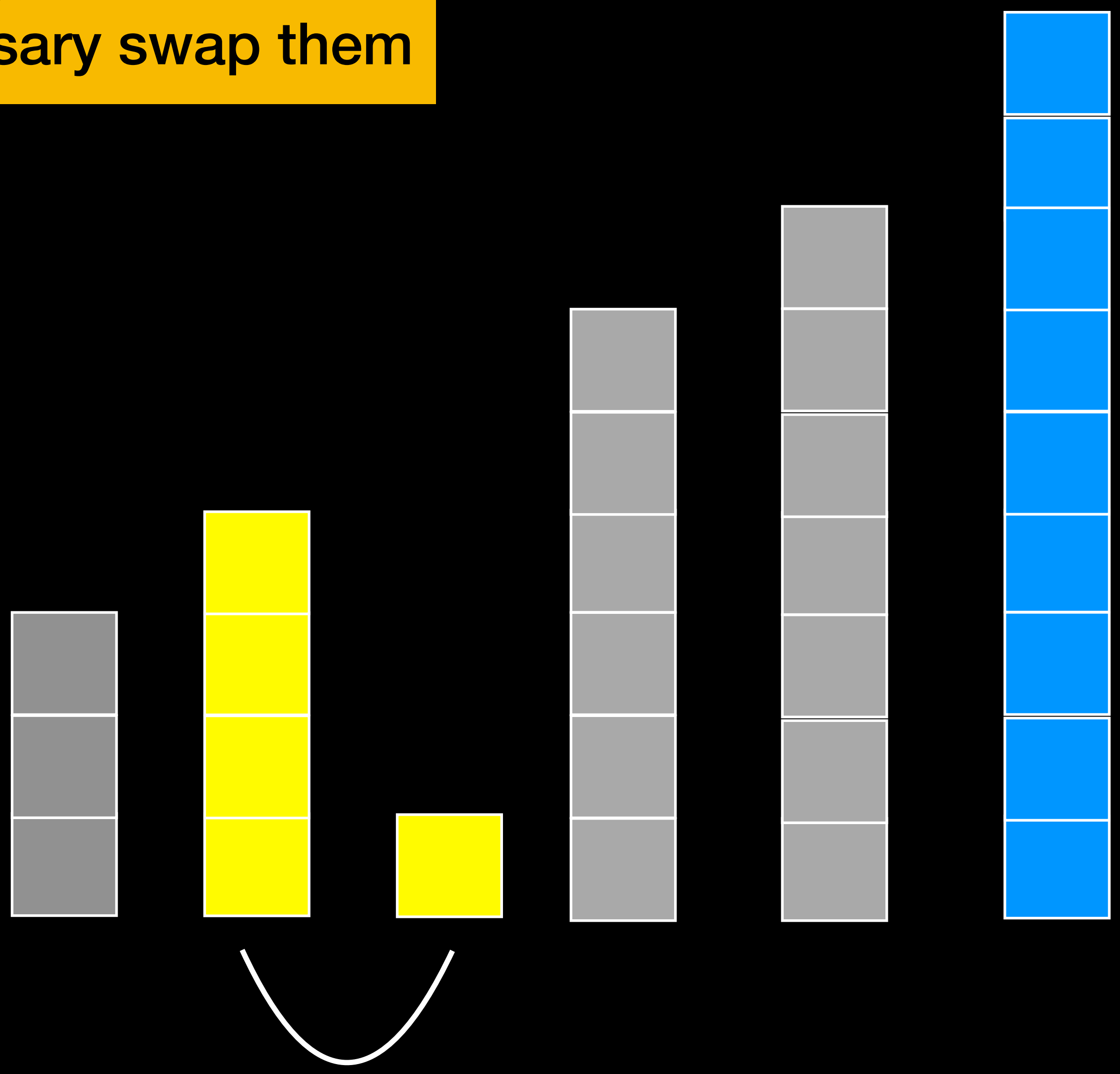


Bubble Sort



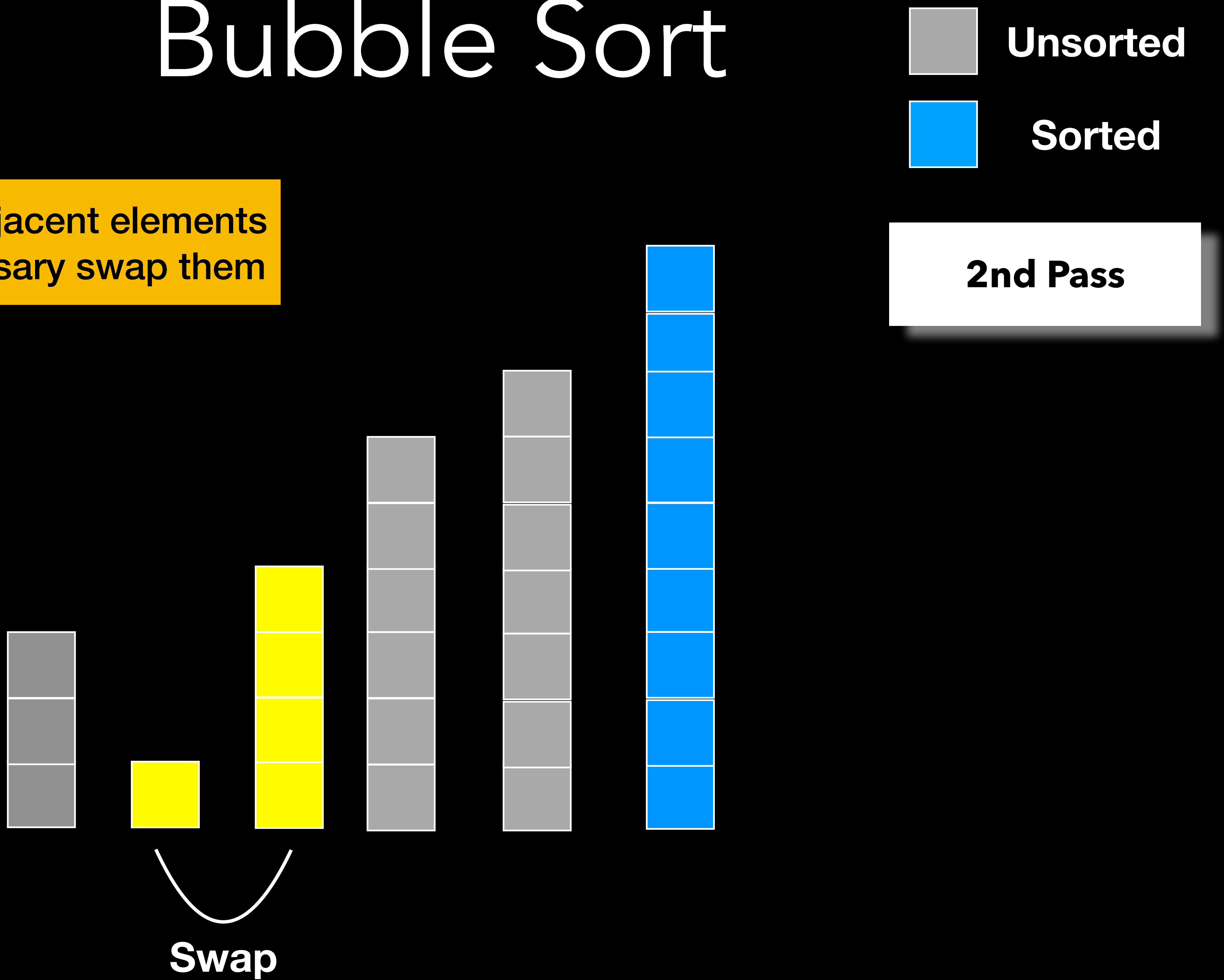
Compare adjacent elements and if necessary swap them

2nd Pass



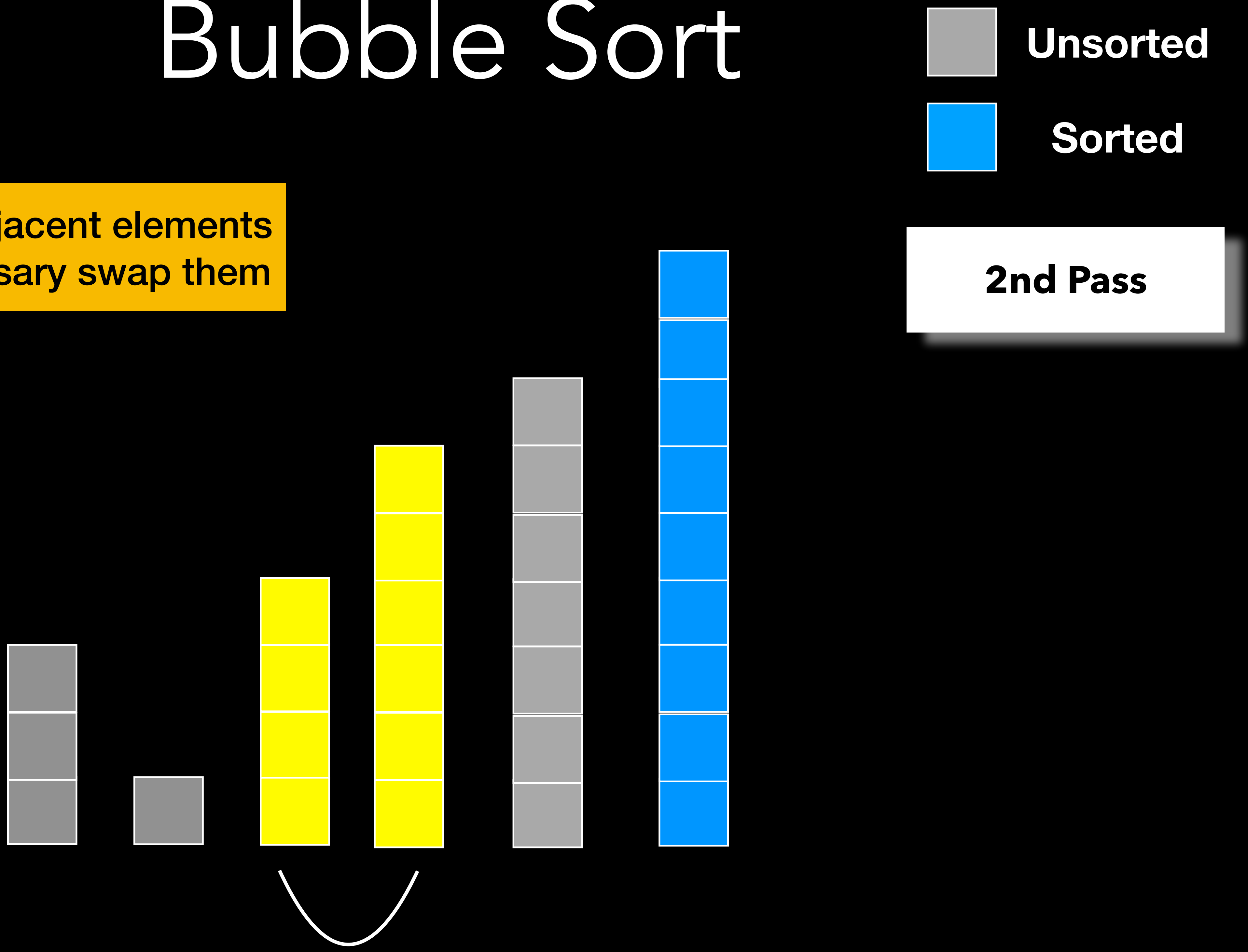
Bubble Sort

Compare adjacent elements and if necessary swap them



Bubble Sort

Compare adjacent elements and if necessary swap them



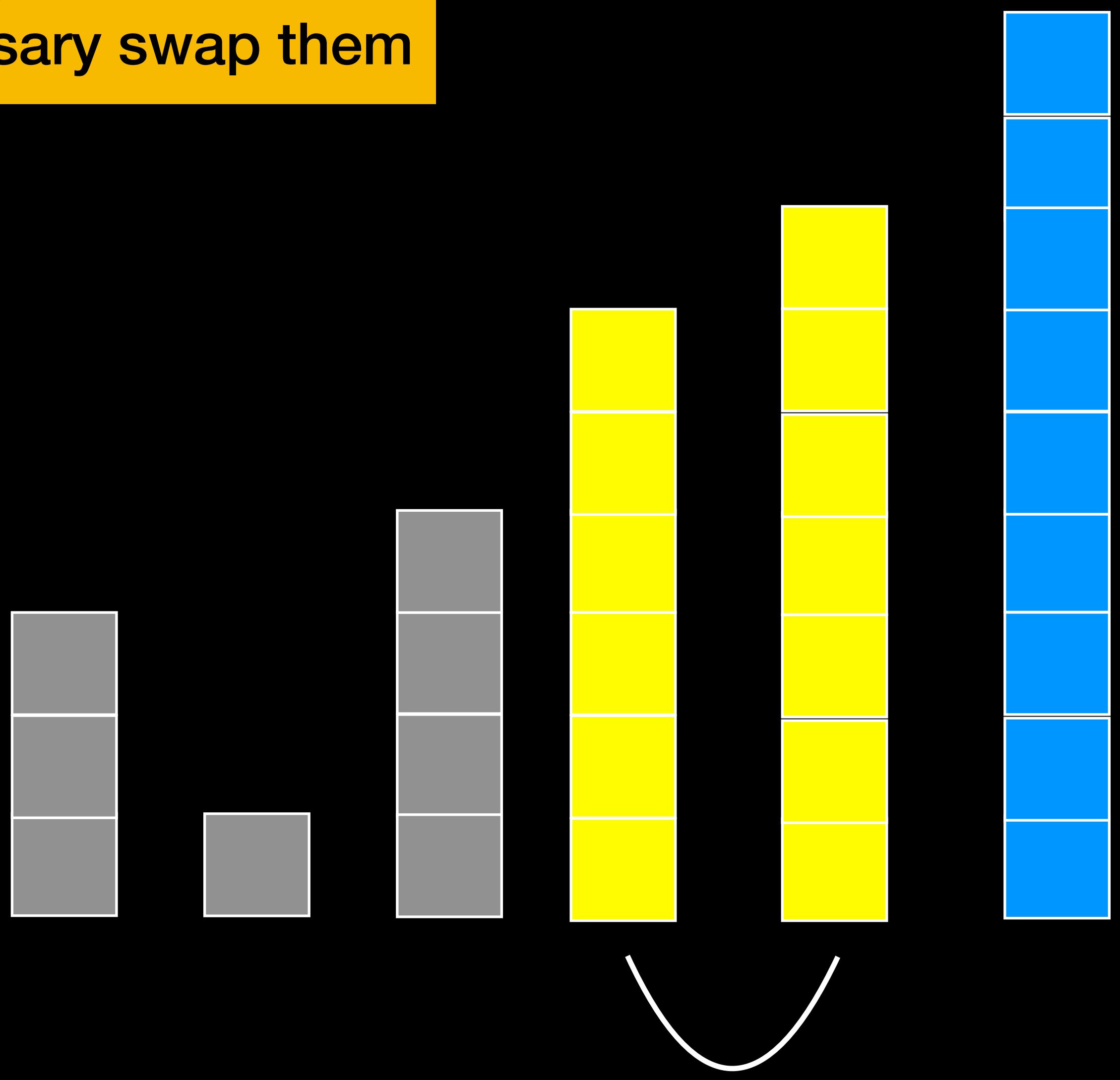
Bubble Sort

Unsorted

Sorted

Compare adjacent elements and if necessary swap them

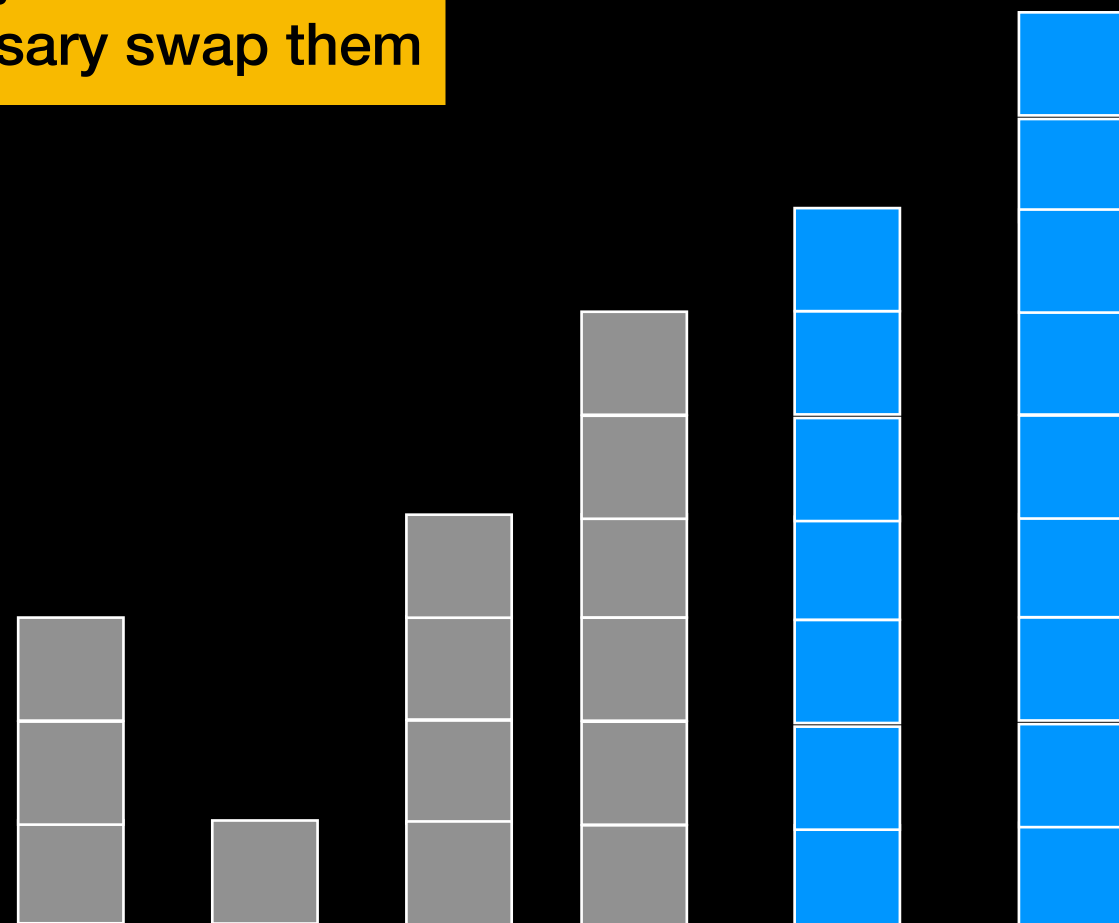
2nd Pass



Bubble Sort

Compare adjacent elements and if necessary swap them

3rd Pass:
Sort **n-2**



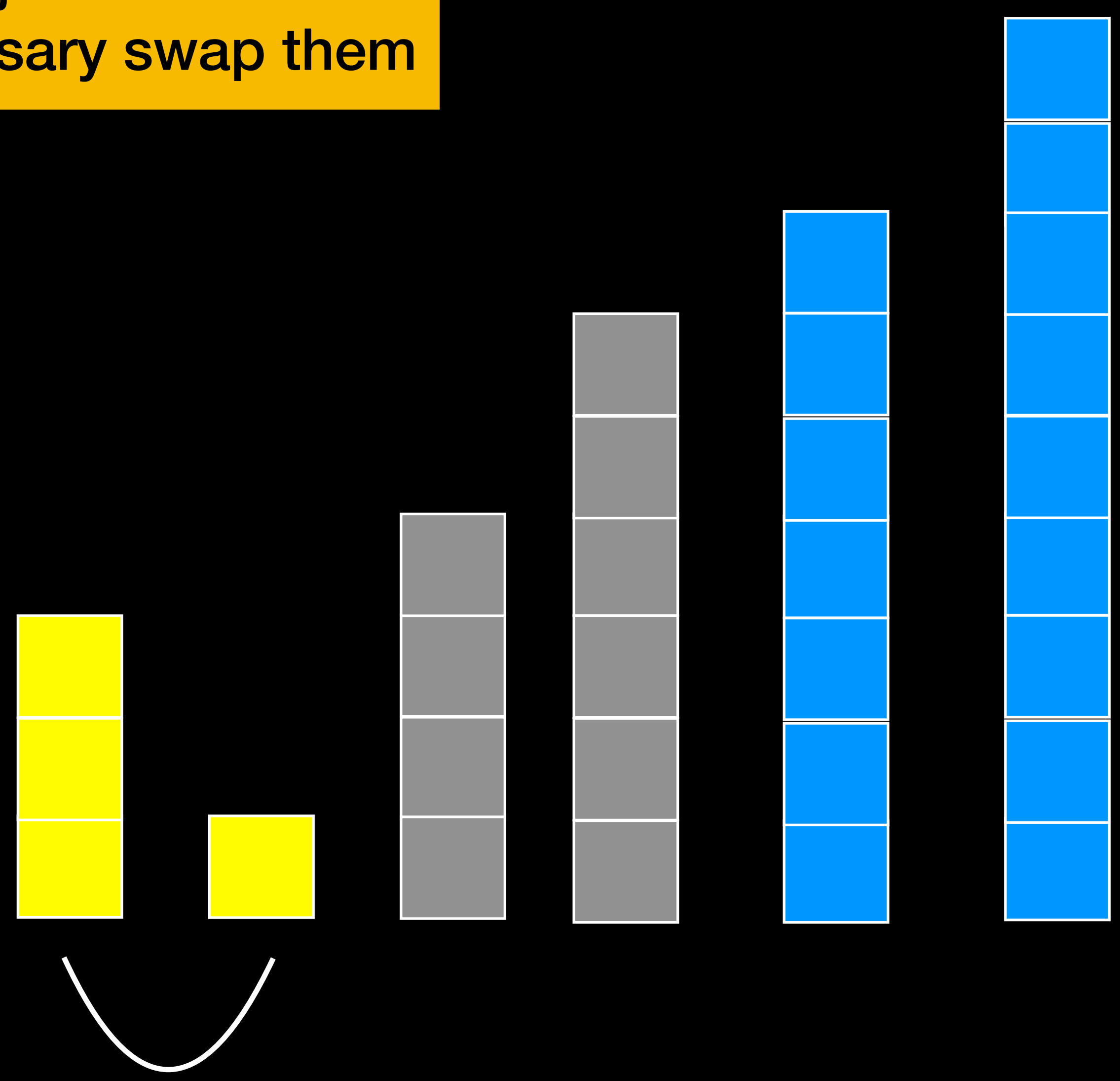
Bubble Sort

Unsorted

Sorted

Compare adjacent elements and if necessary swap them

3rd Pass



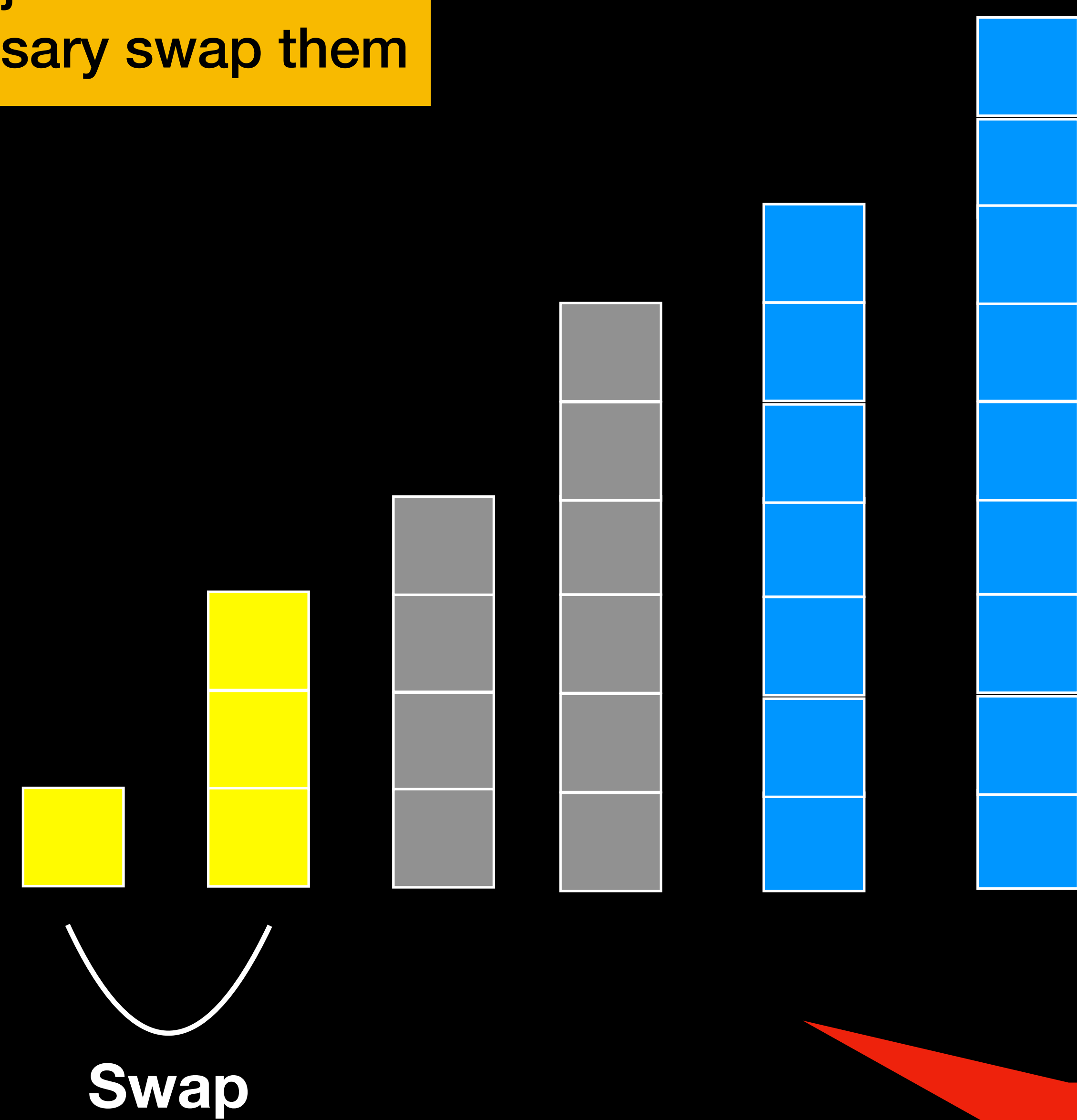
Bubble Sort

Unsorted

Sorted

Compare adjacent elements and if necessary swap them

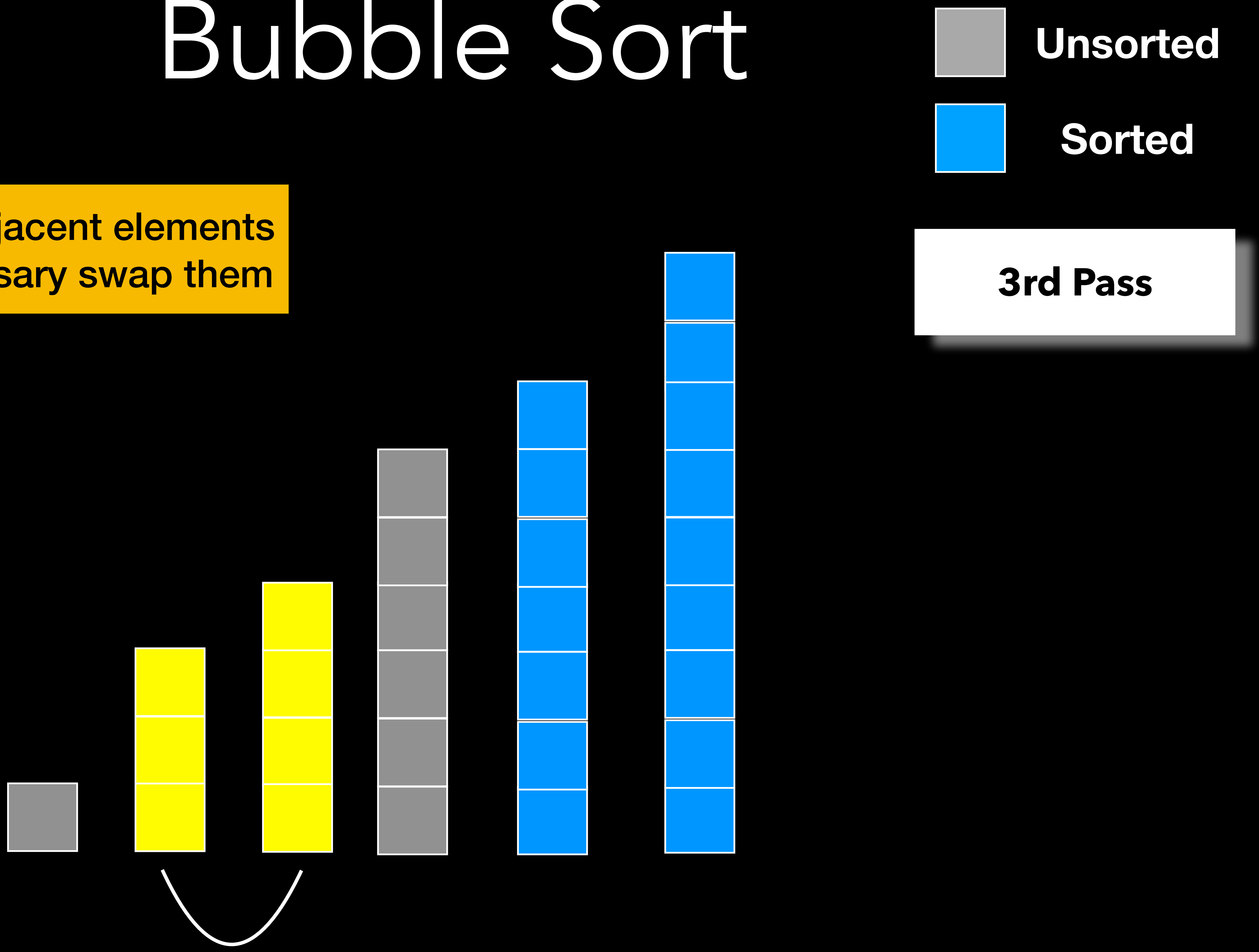
3rd Pass



Array is sorted
But our algorithm doesn't know
It keeps on going

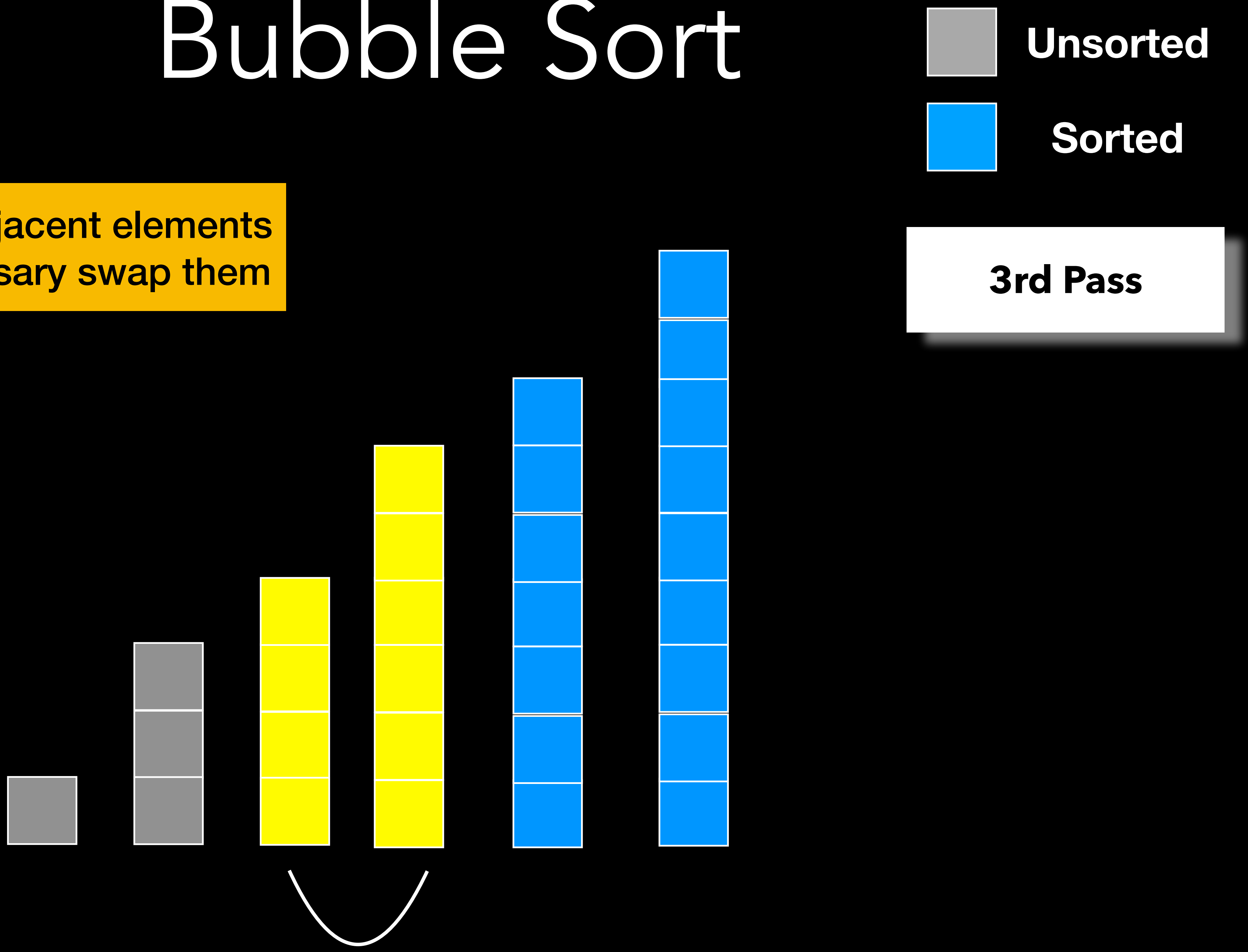
Bubble Sort

Compare adjacent elements and if necessary swap them



Bubble Sort

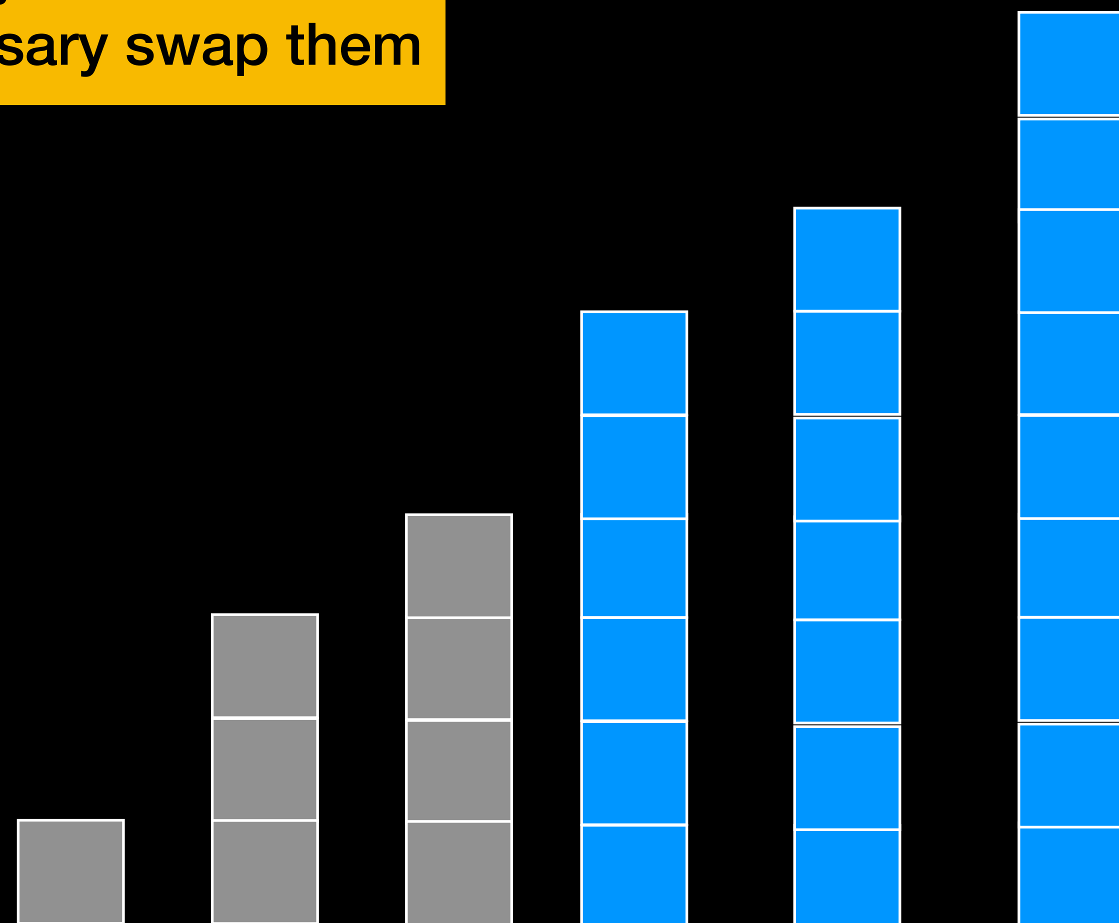
Compare adjacent elements and if necessary swap them



Bubble Sort

Compare adjacent elements and if necessary swap them

4th Pass:
Sort **n-3**



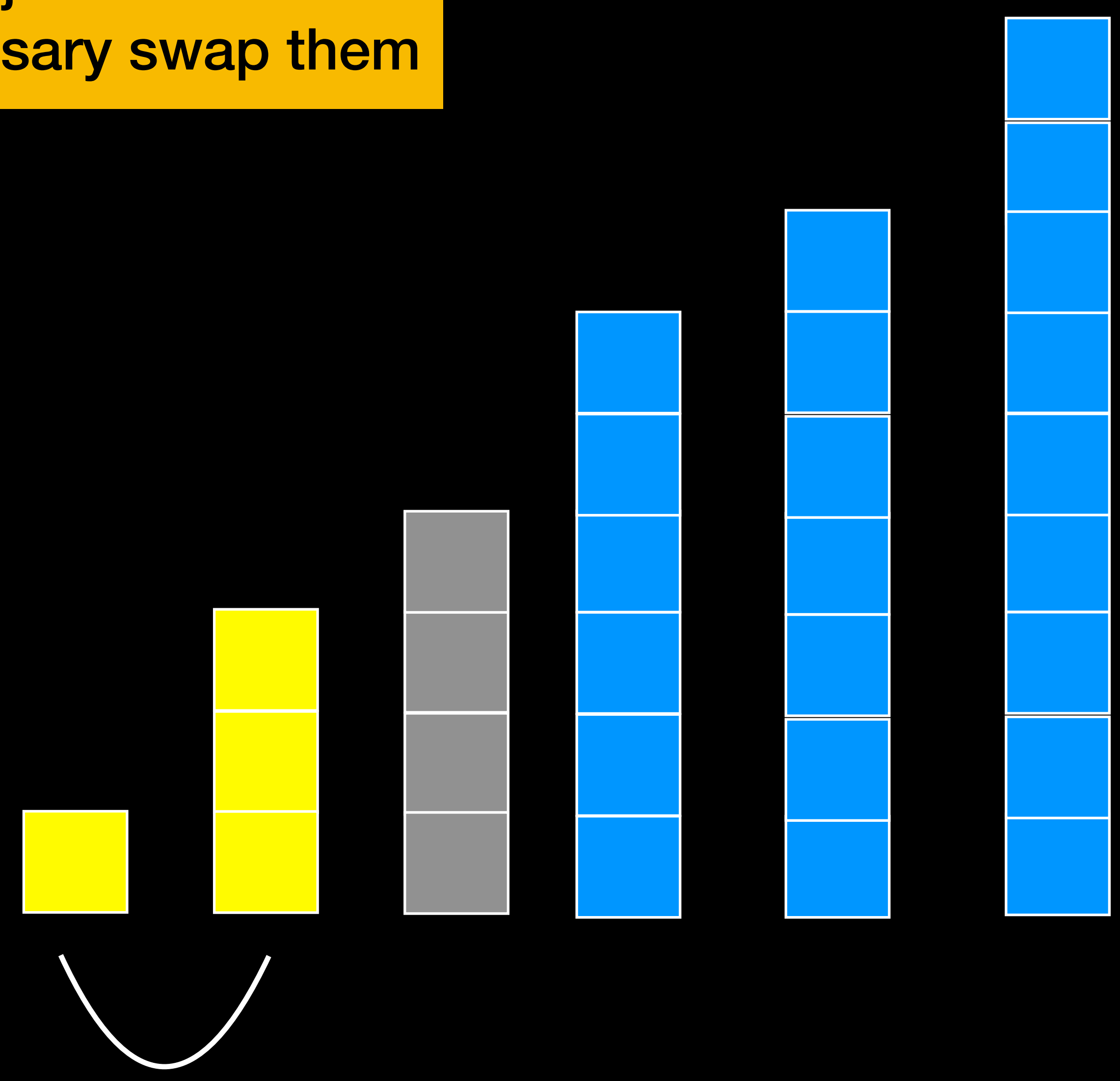
Bubble Sort

Unsorted

Sorted

Compare adjacent elements and if necessary swap them

4th Pass



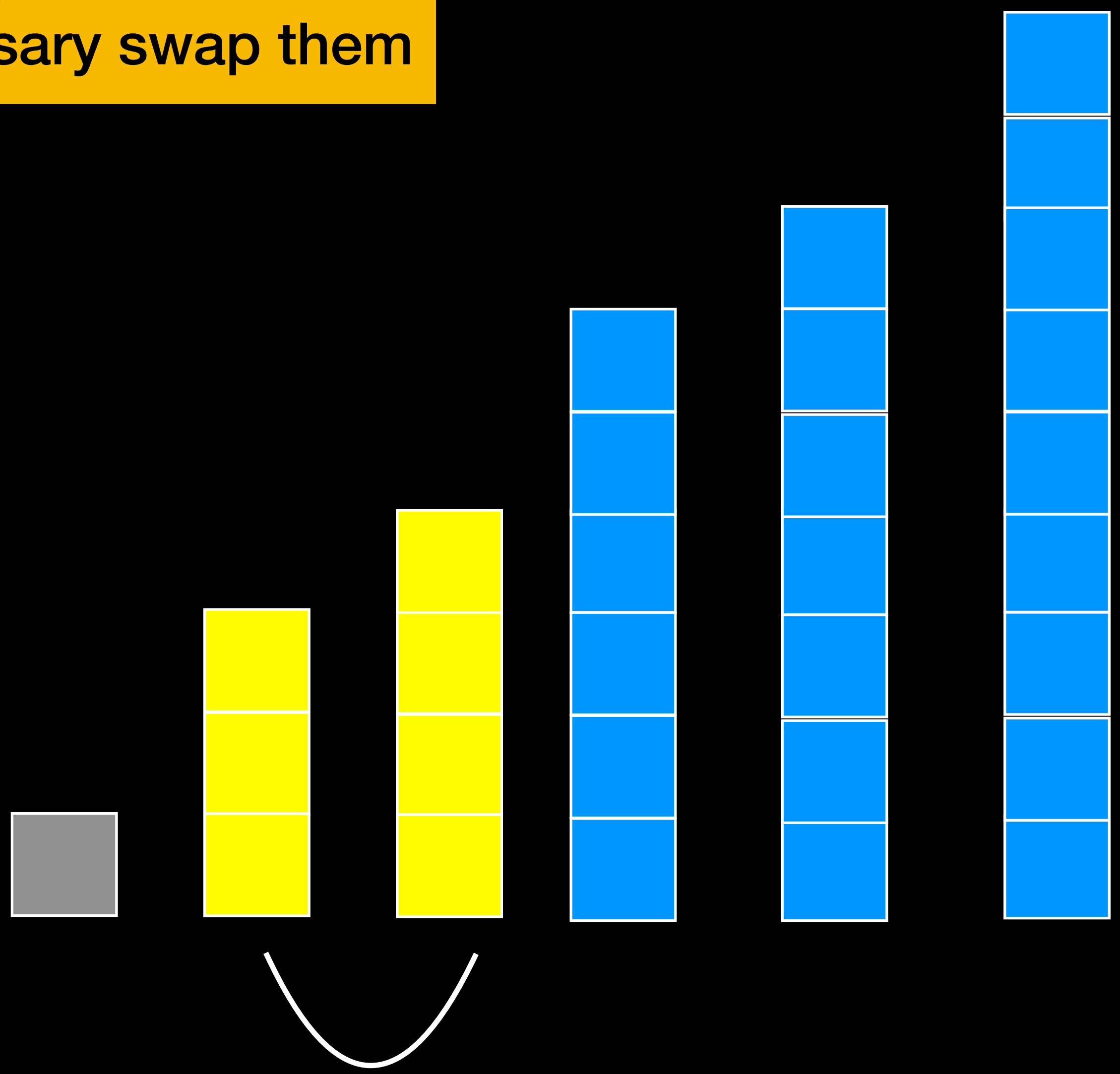
Bubble Sort

Unsorted

Sorted

Compare adjacent elements and if necessary swap them

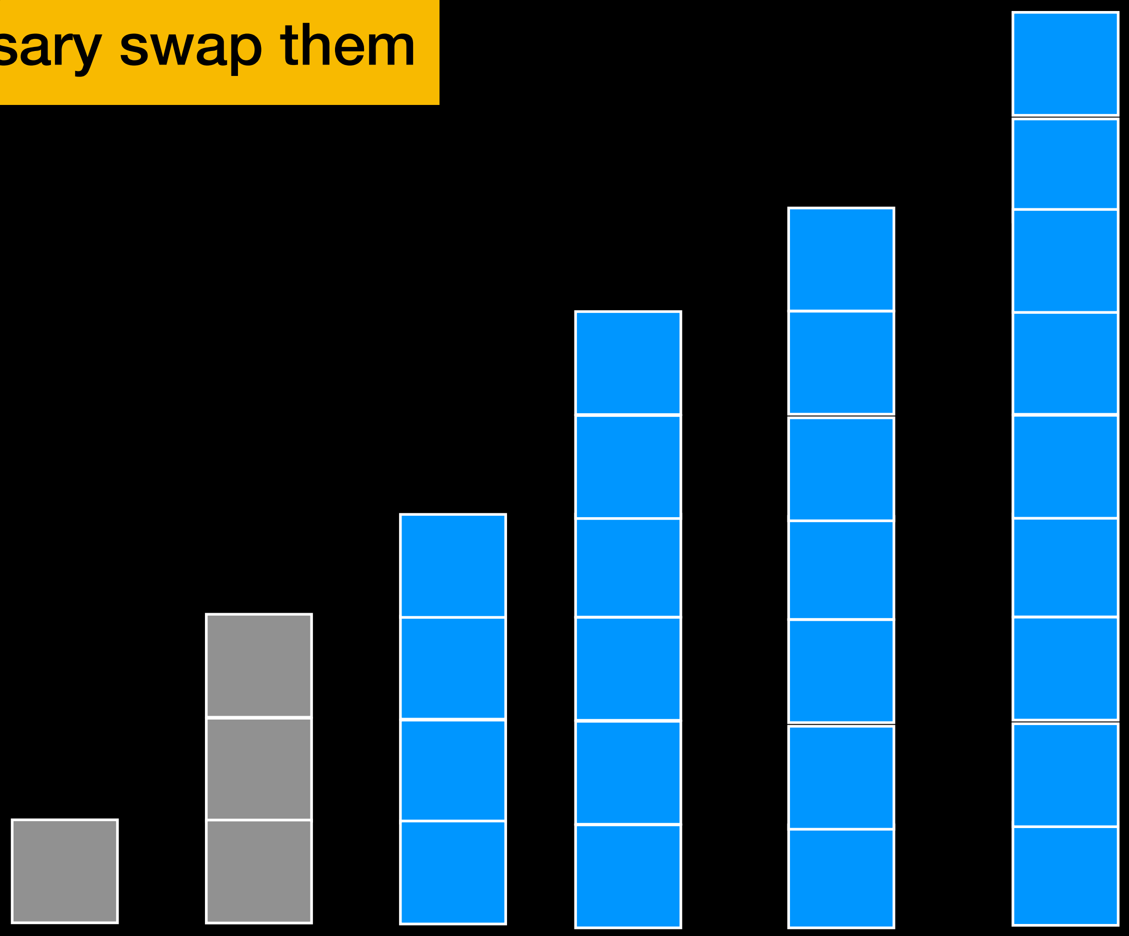
4th Pass



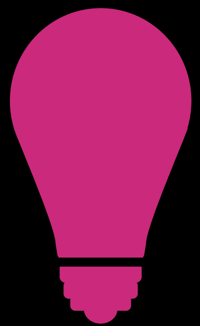
Bubble Sort

Compare adjacent elements and if necessary swap them

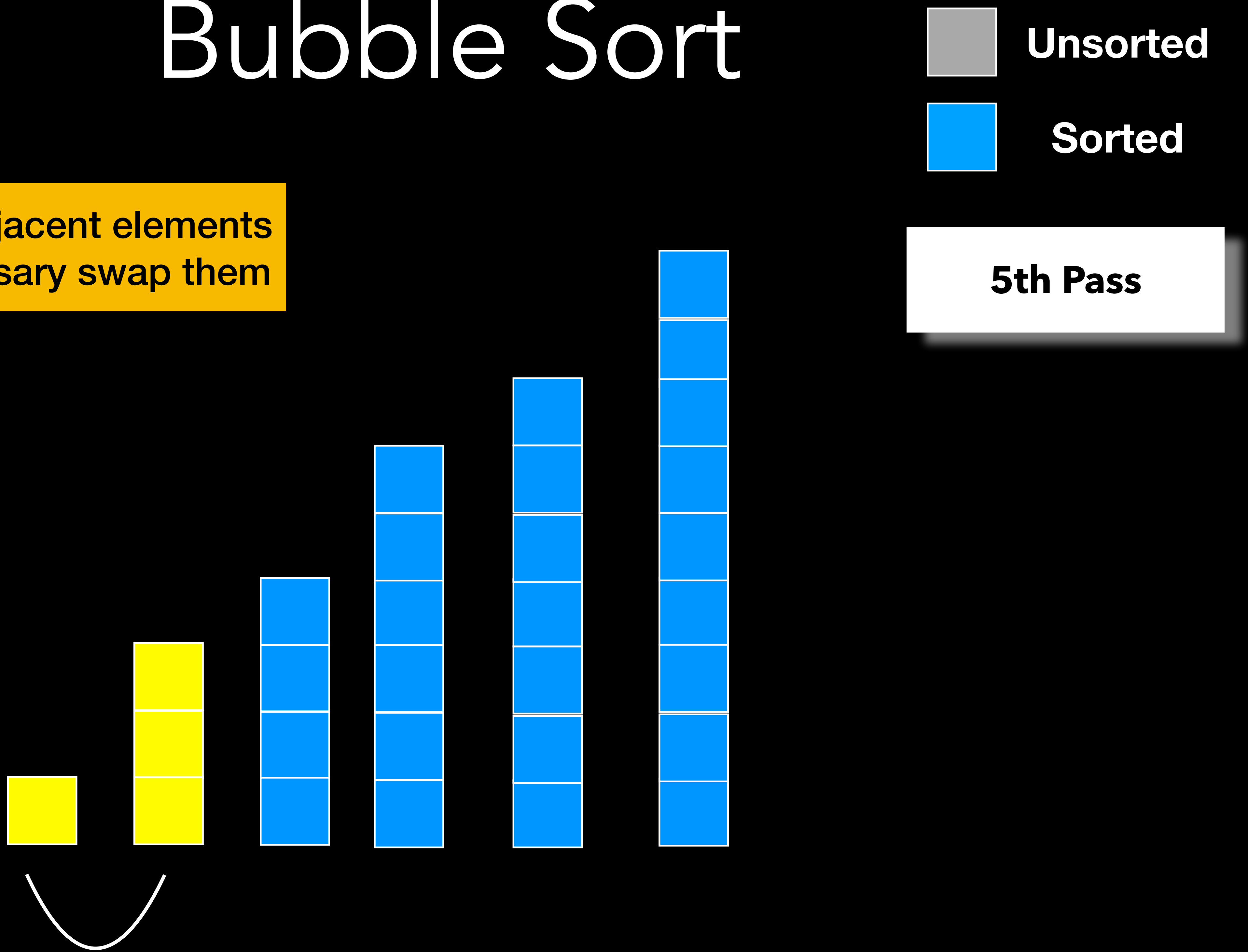
5th Pass:
Sort **n-4**



Bubble Sort



Compare adjacent elements and if necessary swap them



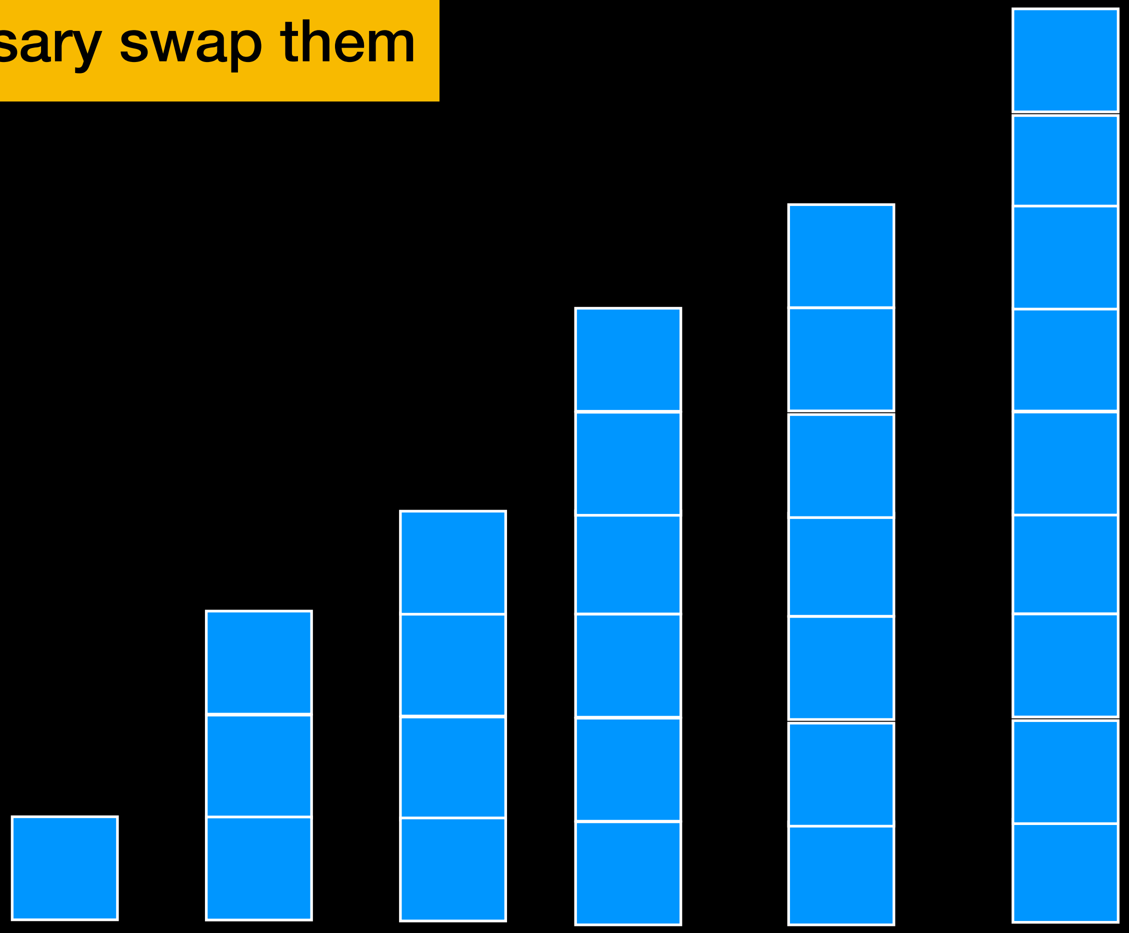
Bubble Sort

Unsorted

Sorted

Compare adjacent elements and if necessary swap them

Done!



Bubble Sort Analysis

How much work?

First pass: **n-1** comparisons and at most **n-1** swaps

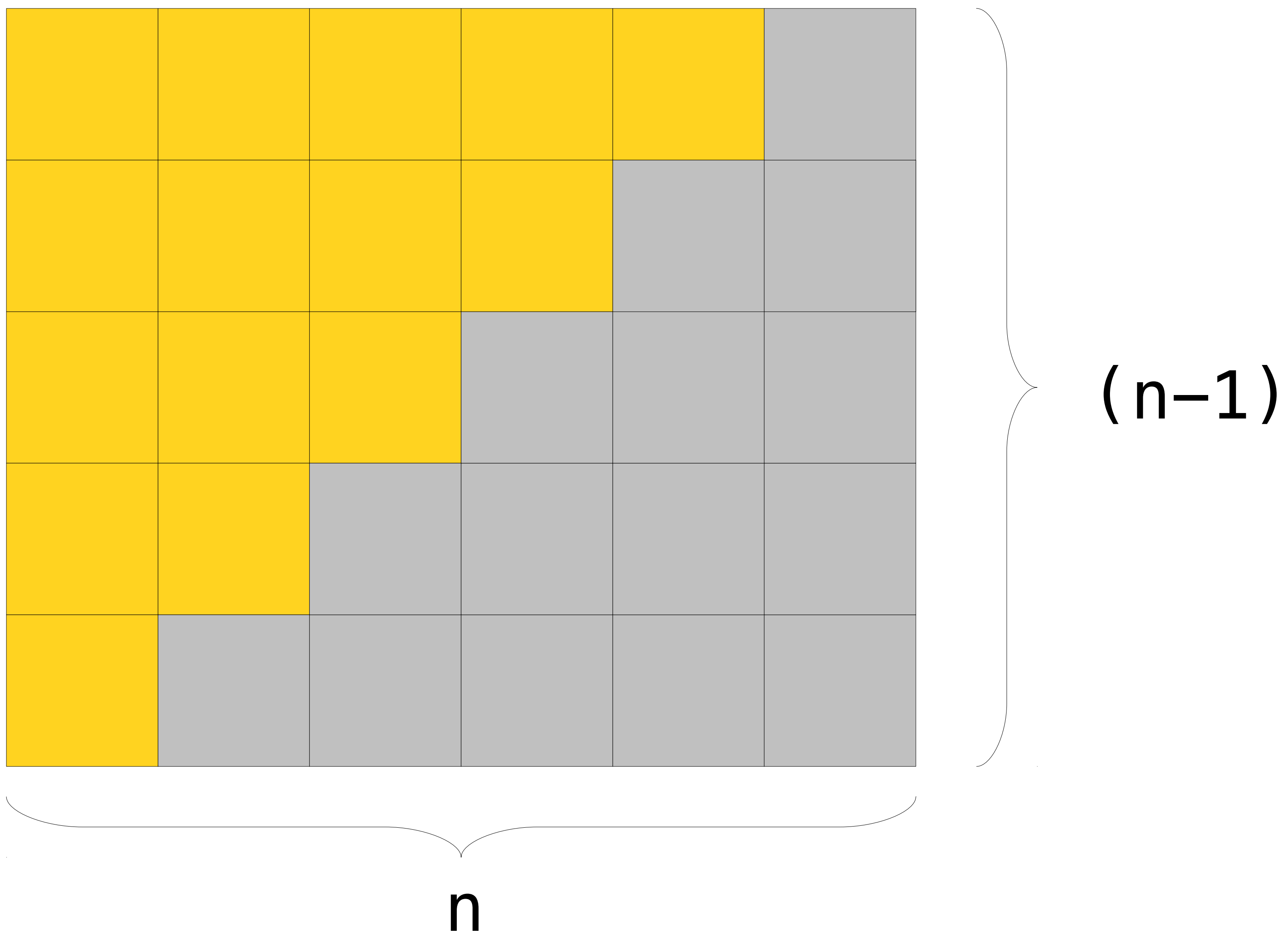
Second pass: **n-2** comparisons and at most **n-2** swaps

Third pass: **n-3** comparisons and at most **n-3** swaps

. . .

Total work: **(n-1) + (n-2) + . . . +1**

$$(n-1) + (n-2) + \ldots + 2 + 1 = n(n-1)/2$$



Bubble Sort Analysis

T(n) = n(n-1) / 2 comparisons + n(n-1) / 2 swaps = O( )?

A swap is usually more than one operation but this simplification does not change the analysis

T(n) = 2(n(n-1) / 2)= O( )?

Bubble Sort Analysis

$T(n)$ = n(n-1) / 2 comparisons + n(n-1) / 2 swaps = O( )?

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$T(n) = 2(n(n-1) / 2)= O( )$?

$T(n) = 2((n^2-n) / 2)= O( )$?

Bubble Sort Analysis

$T(n)$ = n(n-1) / 2 comparisons + n(n-1) / 2 swaps = O( )?

A swap is usually more than one operation but this simplification does not change the analysis

$T(n) = 2(n(n-1) / 2)= O( )?$

$T(n) = 2((n^2-n) / 2)= O( )?$

$T(n) = n^2-n = O( )?$

Ignore non-dominant terms

Bubble Sort Analysis

$T(n) = n(n\text{-}1) / 2$ comparisons $+ n(n\text{-}1) / 2$ swaps $= O(\ )$?

A swap is usually more than one operation but this simplification does not change the analysis

$T(n) = 2(\ n(n\text{-}1) / 2\ ) = O(\ )$?

$T(n) = 2(\ (n^2\text{-}n) / 2\ ) = O(\ )$?

$T(n) = n^2\text{-}n = O(\ \mathbf{n^2})$

Bubble Sort run time is **$O(n^2)$**

Optimize!

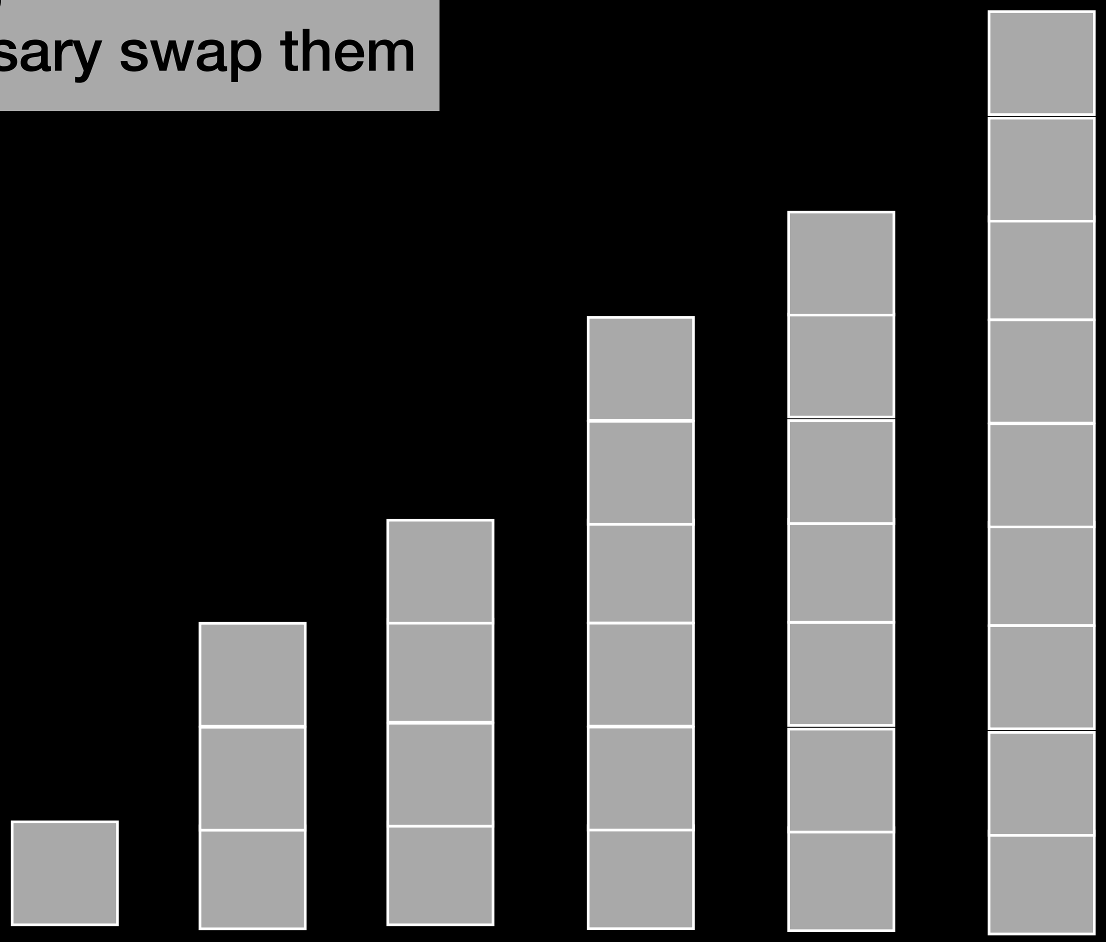
Easy to check:

if there are no swaps in any given pass

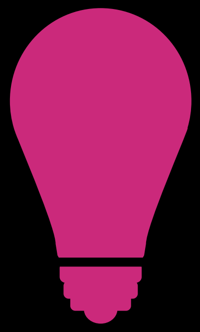
stop because it is sorted

Bubble Sort

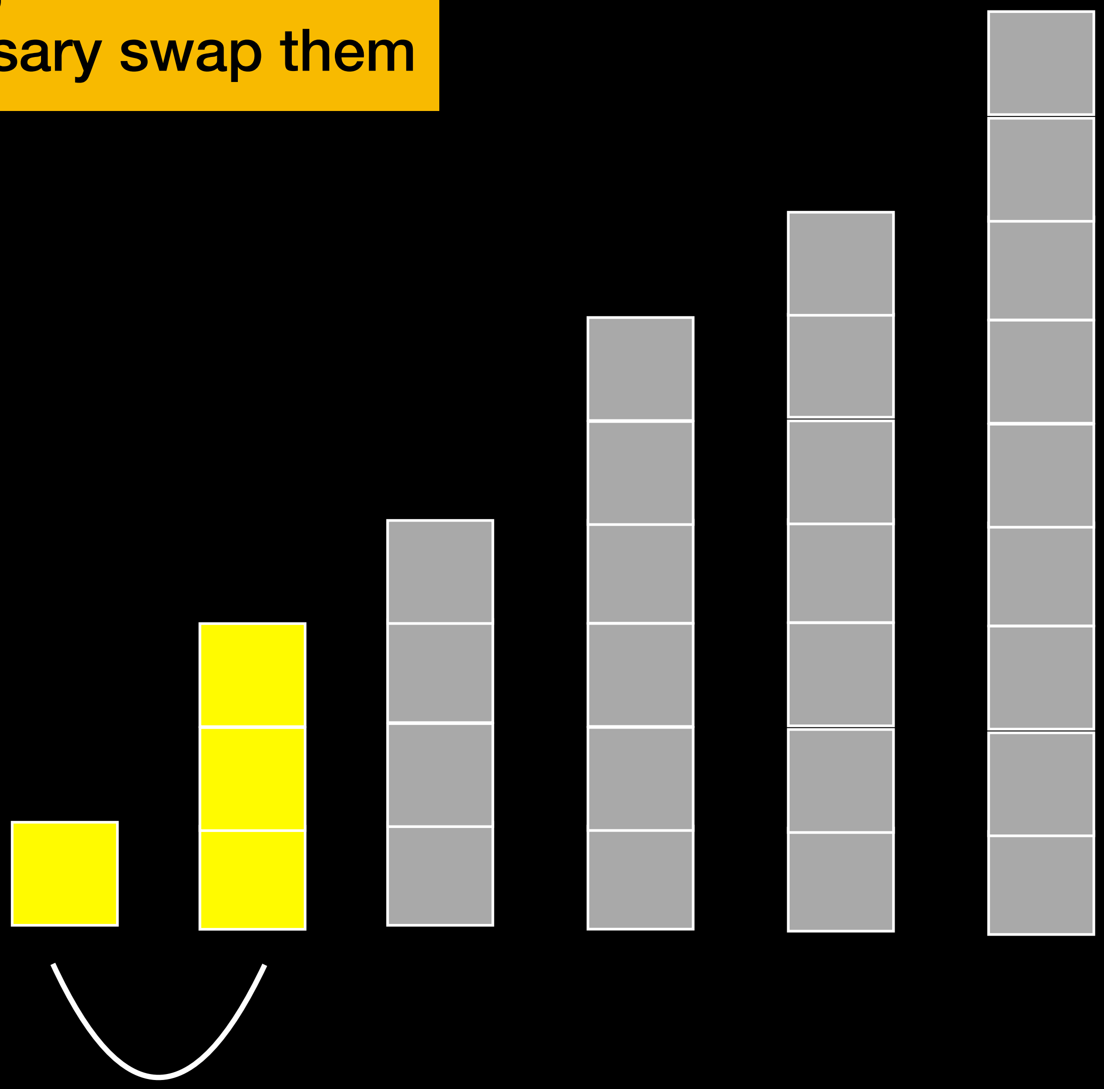
Compare adjacent elements and if necessary swap them



Bubble Sort

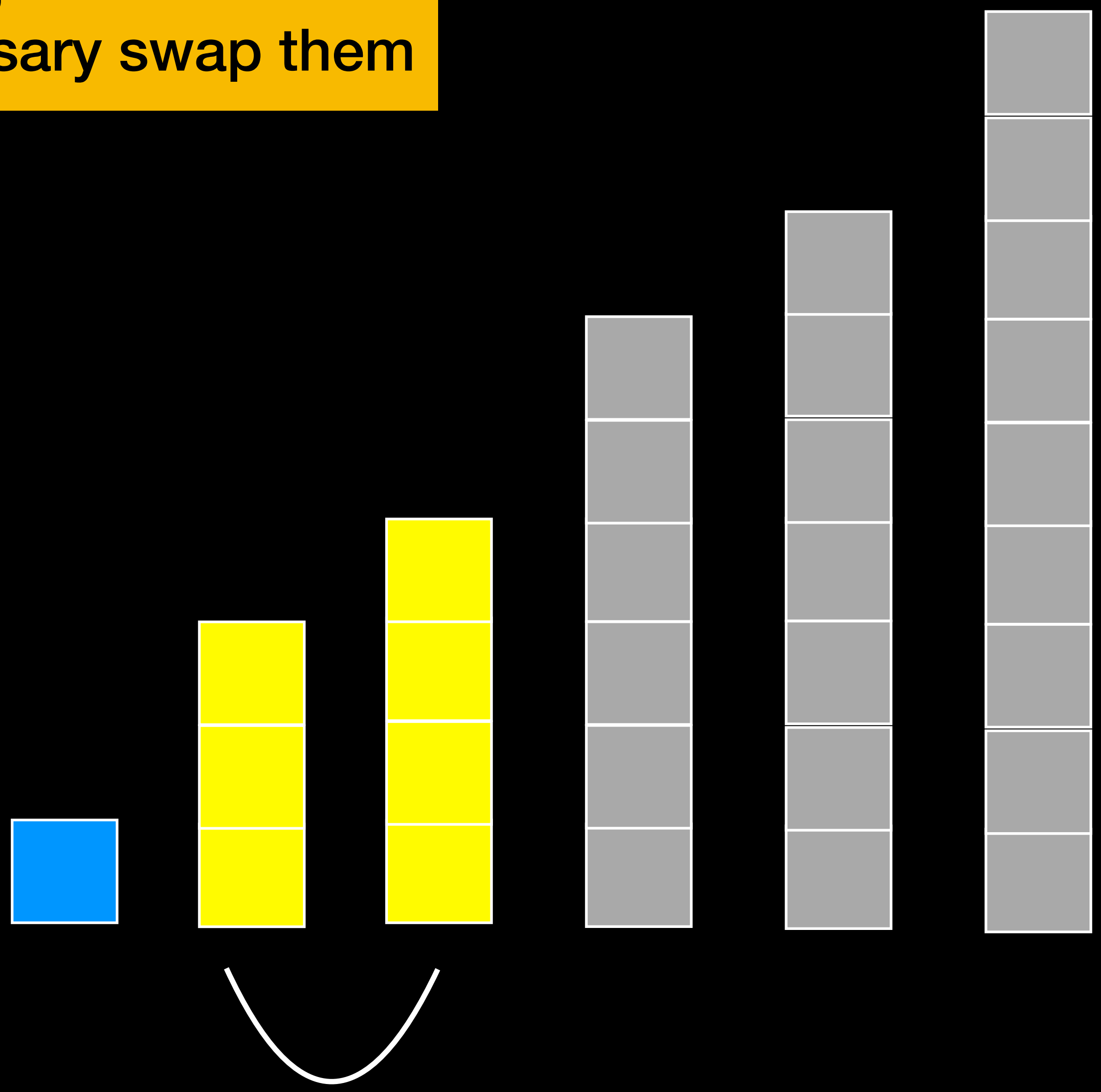


Compare adjacent elements and if necessary swap them



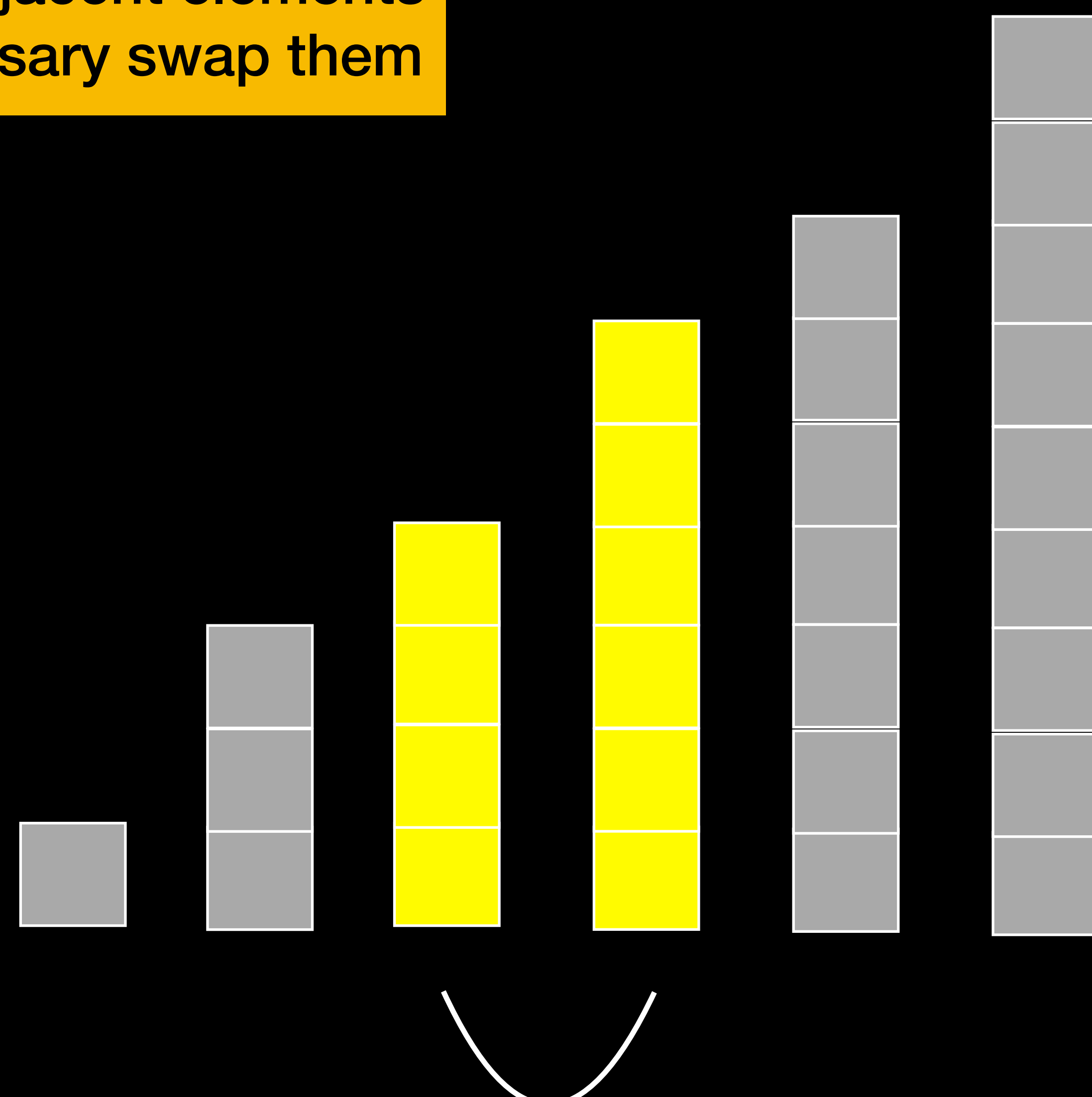
Bubble Sort

Compare adjacent elements and if necessary swap them



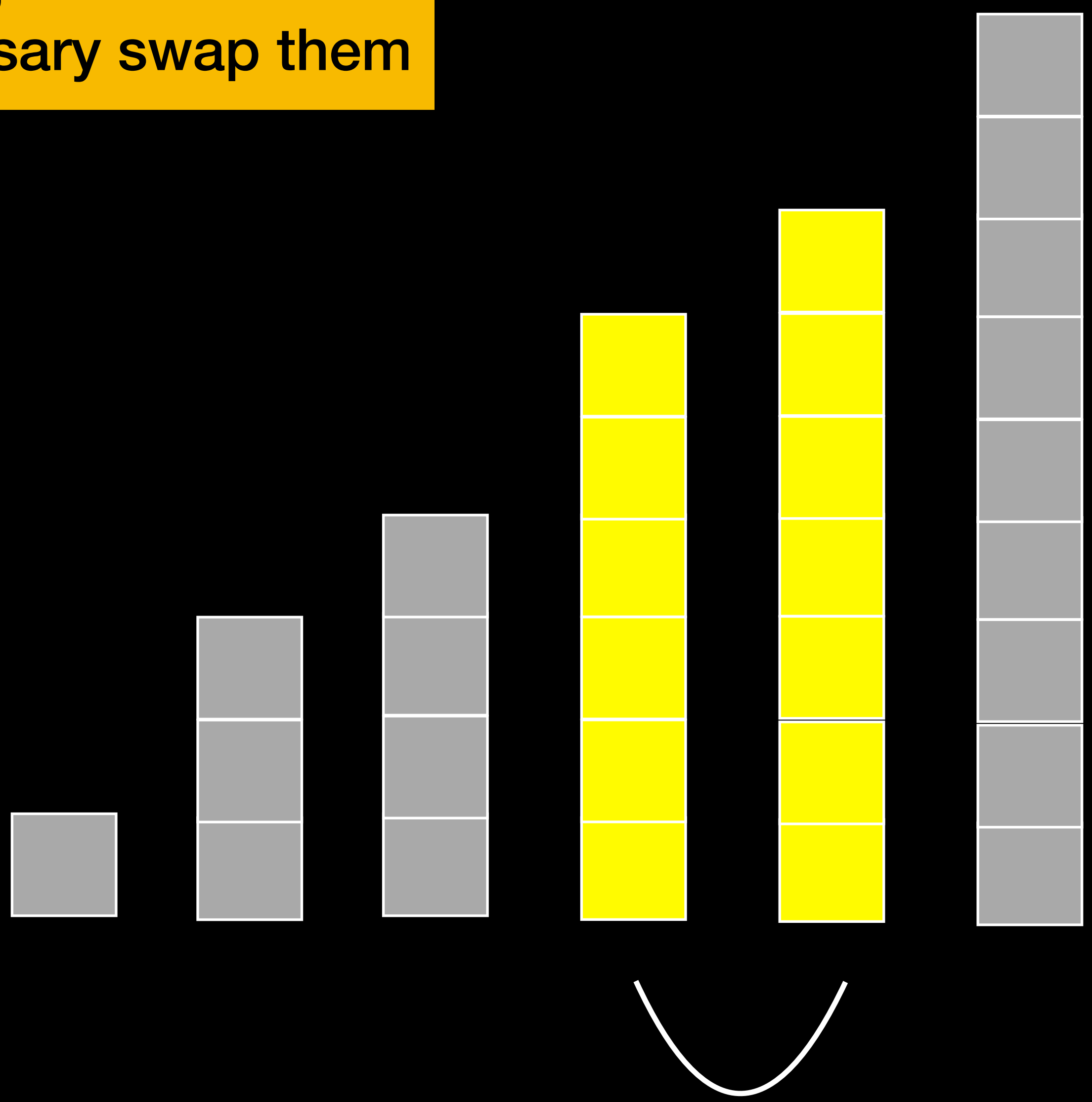
Bubble Sort

Compare adjacent elements and if necessary swap them



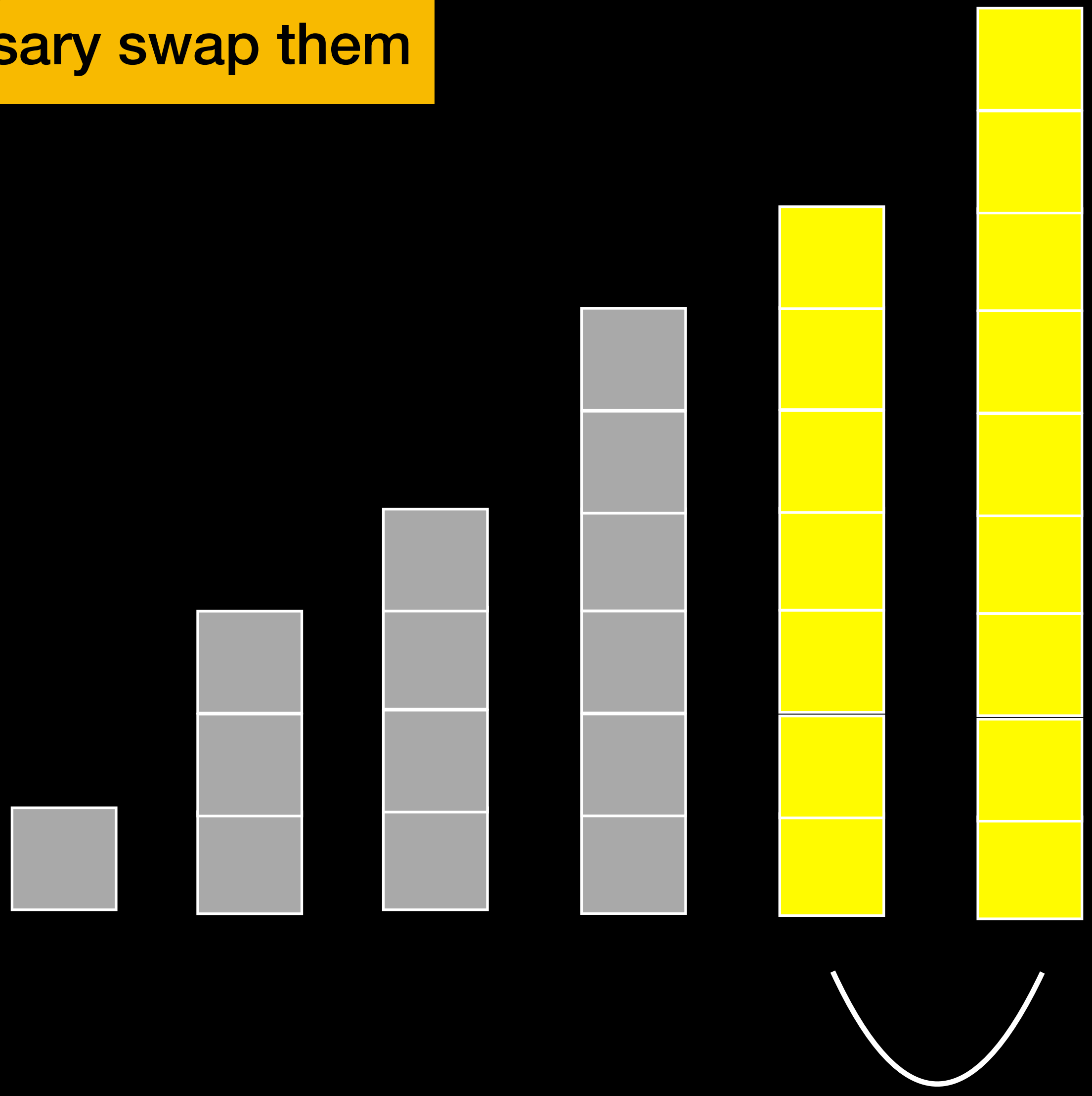
Bubble Sort

Compare adjacent elements and if necessary swap them

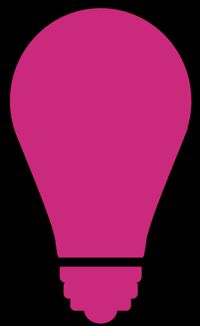


Bubble Sort

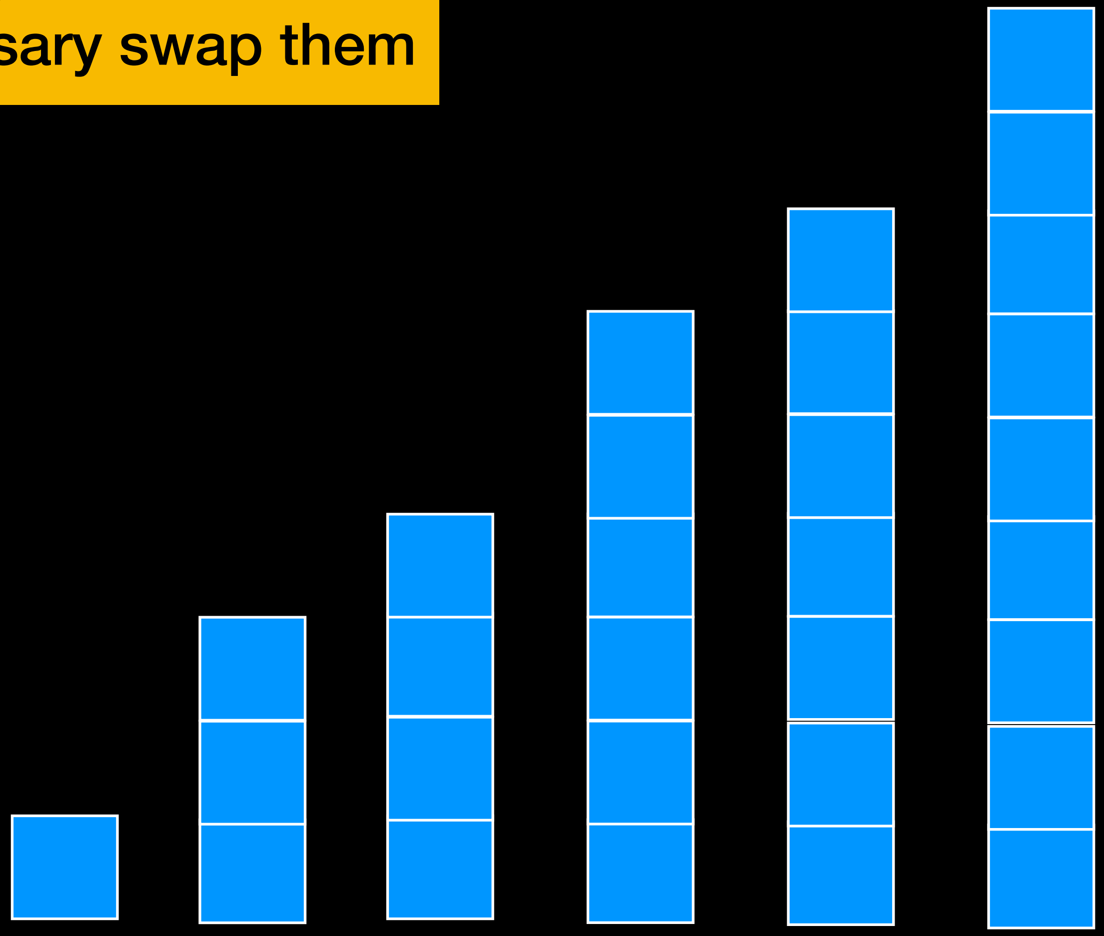
Compare adjacent elements and if necessary swap them



Bubble Sort



Compare adjacent elements and if necessary swap them



```
template <class Comparable>
void bubbleSort(const std::vector<Comparable>& the_array)
{
   int size = the_array.size();
   bool swapped = true; // Assume unsorted
   int pass = 1;
   while (swapped && (pass < size))
   {
      // At this point, if pass > 1 the_array[size+1-pass … size-1] is sorted
      // and all of its entries are > the entries in the_array[0 ... size-pass]
       swapped = false;
      for (int index = 0; index < size - pass; index++)
      {
         // At this point, all entries in the_array[0 ... index-1]
         // are <= the_array[index]
         if (the_array[index] > the_array[index+1])
         {
             std::swap(the_array[index], the_array[index+1]); //swap
             swapped = true; // indicates array not yet sorted
         }// end if
      }  // end for
      // Assertion: the_array[0 ... size-pass-1] < the_array[size-pass]

      pass++;
   }  // end while
}  // end bubbleSort
```

```
template <class Comparable>
void bubbleSort(const std::vector<Comparable>& the_array)
{
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      // At this point, if pass > 1 the_array[size+1-pass … size-1] is sorted
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      {
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         if (the_array[index] > the_array[index+1])
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             std::swap(the_array[index], the_array[index+1]); //swap
             swapped = true; // indicates array not yet sorted
         }// end if
      }  // end for
      // Assertion: the_array[0 ... size-pass-1] < the_array[size-pass]

      pass++;
   }  // end while
}  // end bubbleSort
```

Pass O(n)

O(n)

$O(n^2)$

Bubble Sort Analysis

Execution time DOES depend on initial arrangement of data

Worst case: $O(n^2)$ comparisons and data moves

Best case: $O(n)$ comparisons and data moves

Stable

If array is already sorted bubble sort will stop after first pass and no swaps => good choice for small n and data likely somewhat sorted

Raise your hand if you had
Bubble Sort

https://www.youtube.com/watch?v=lyZQPjUT5B4

Insertion Sort

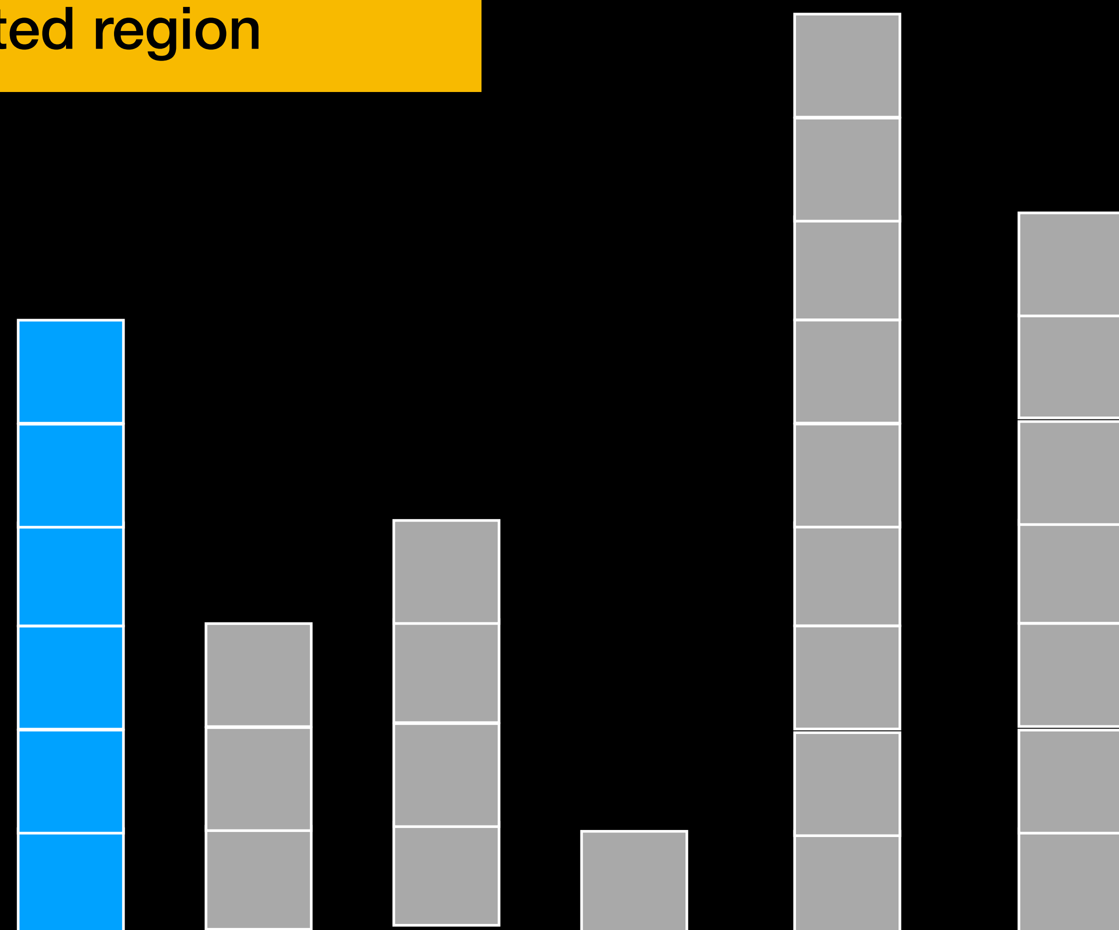
Insertion Sort

Unsorted

Sorted

Pick first element in unsorted region and put it in right place in sorted region

1st Pass



Insertion Sort

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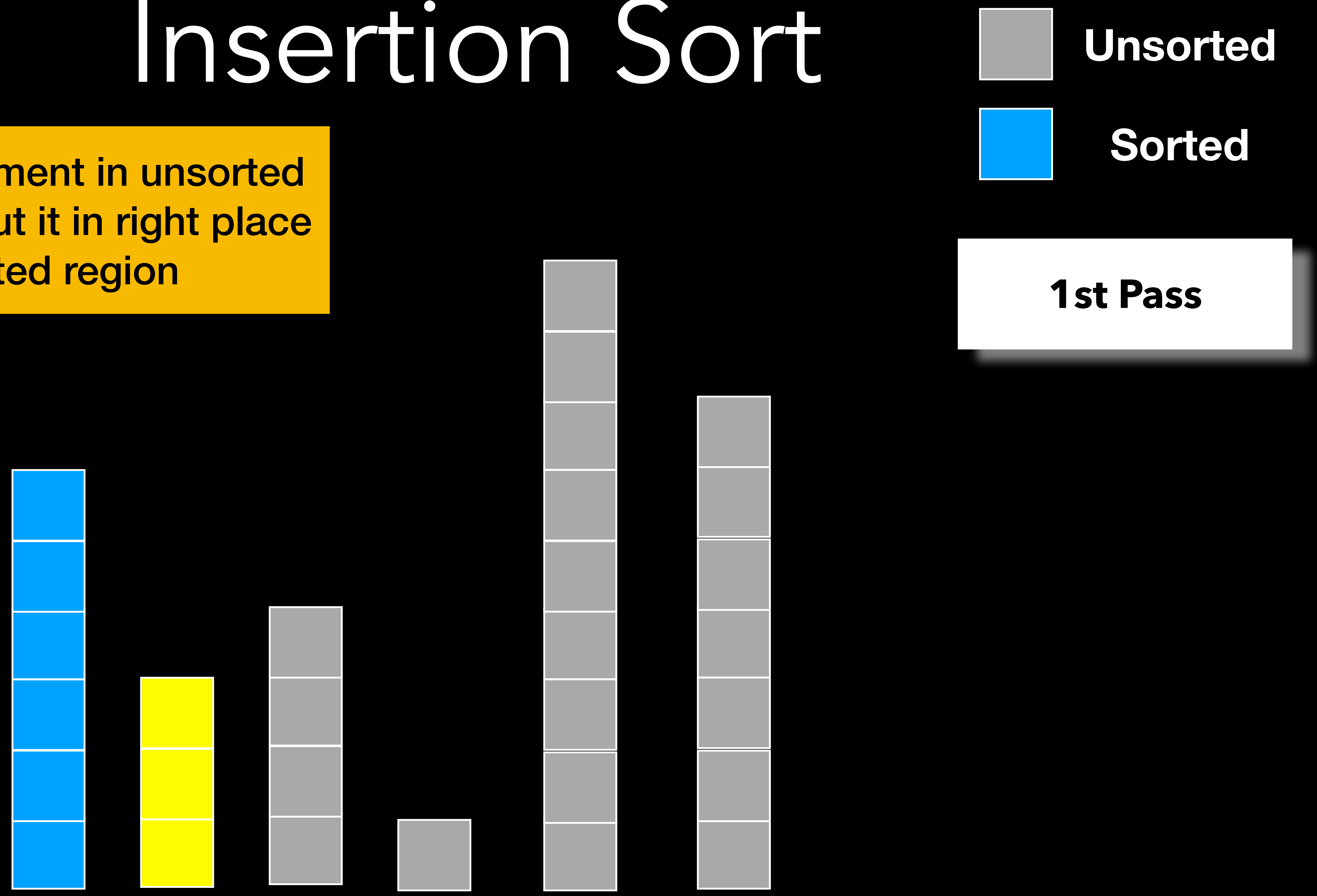

Insertion Sort

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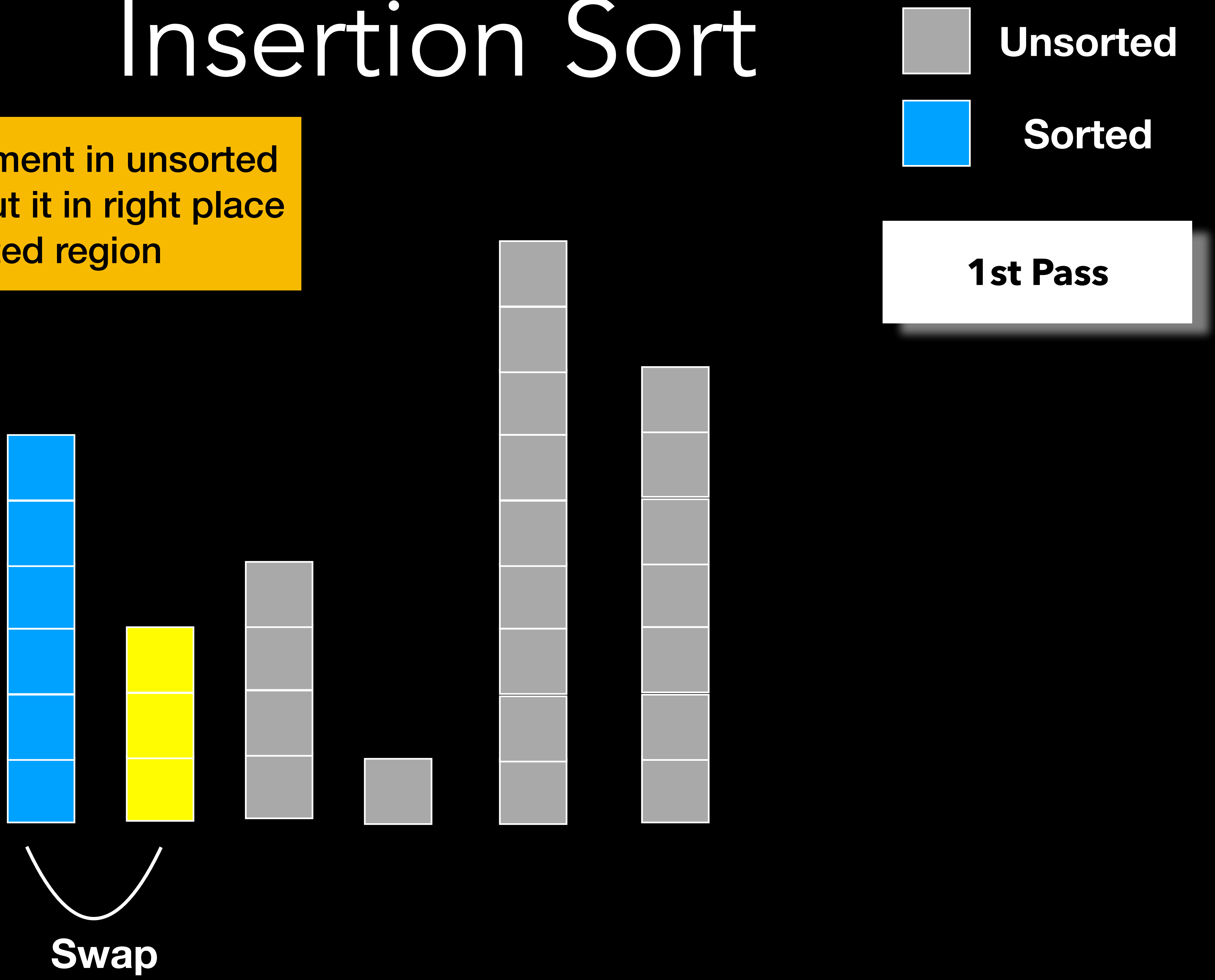


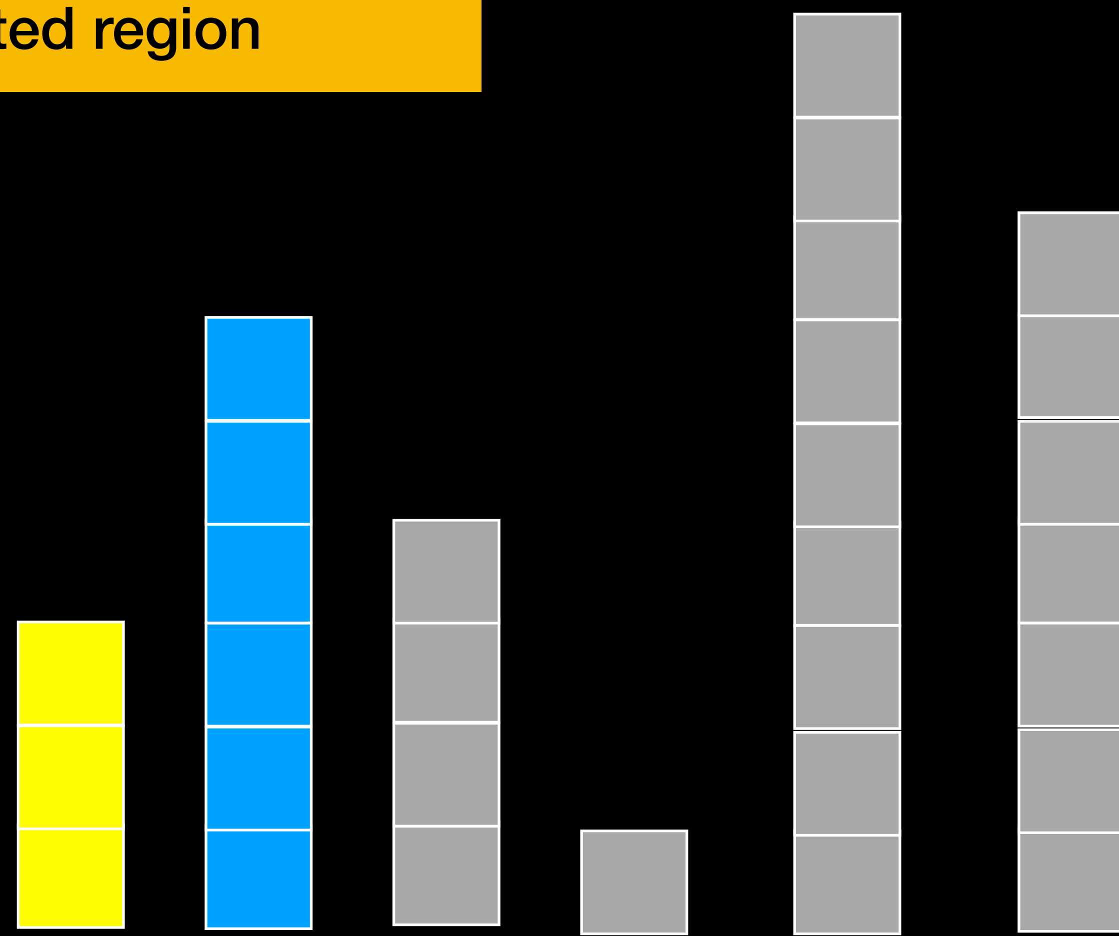
Insertion Sort

Unsorted

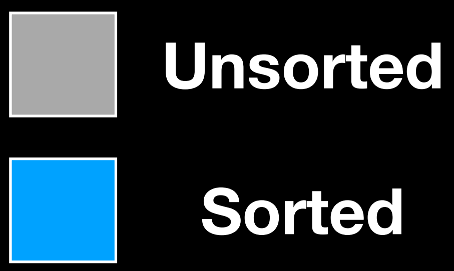
Sorted

Pick first element in unsorted region and put it in right place in sorted region

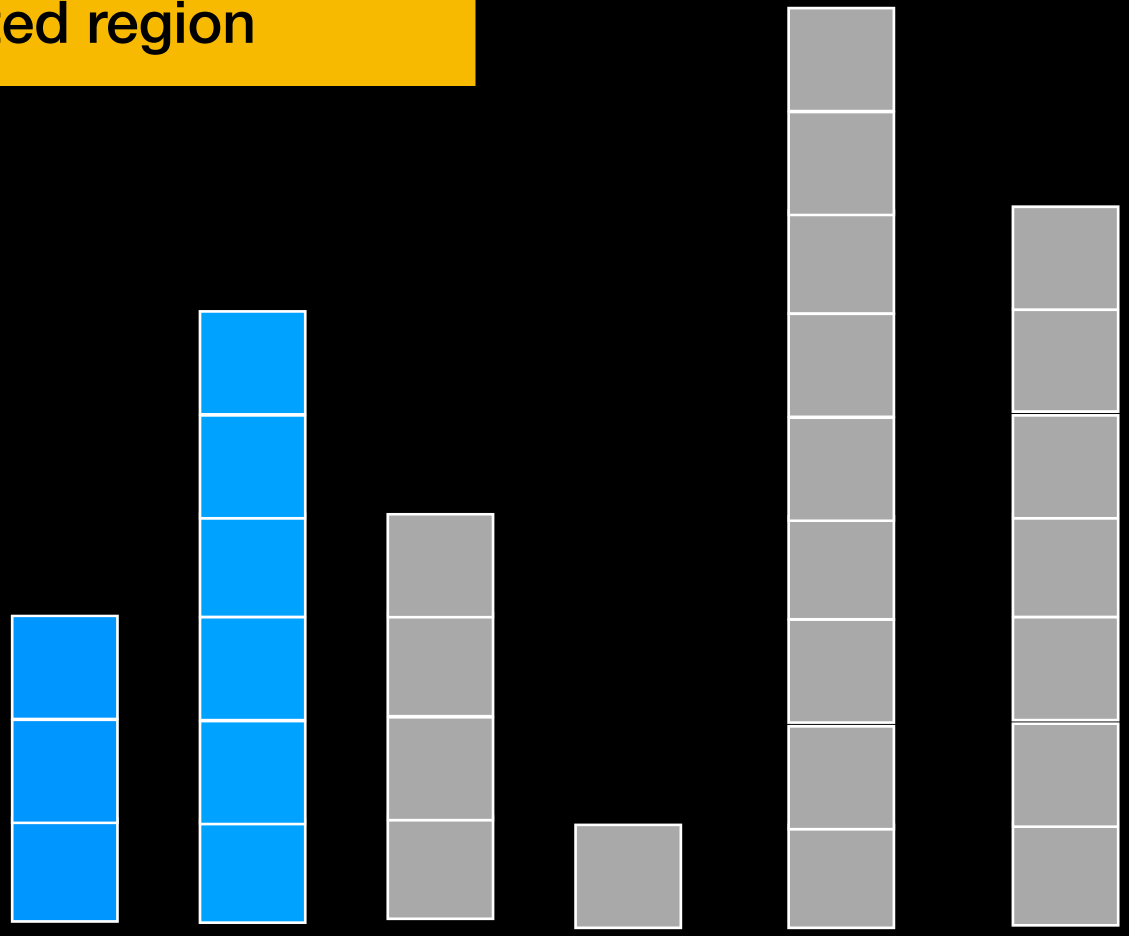
1st Pass



Insertion Sort



Pick first element in unsorted region and put it in right place in sorted region



Insertion Sort

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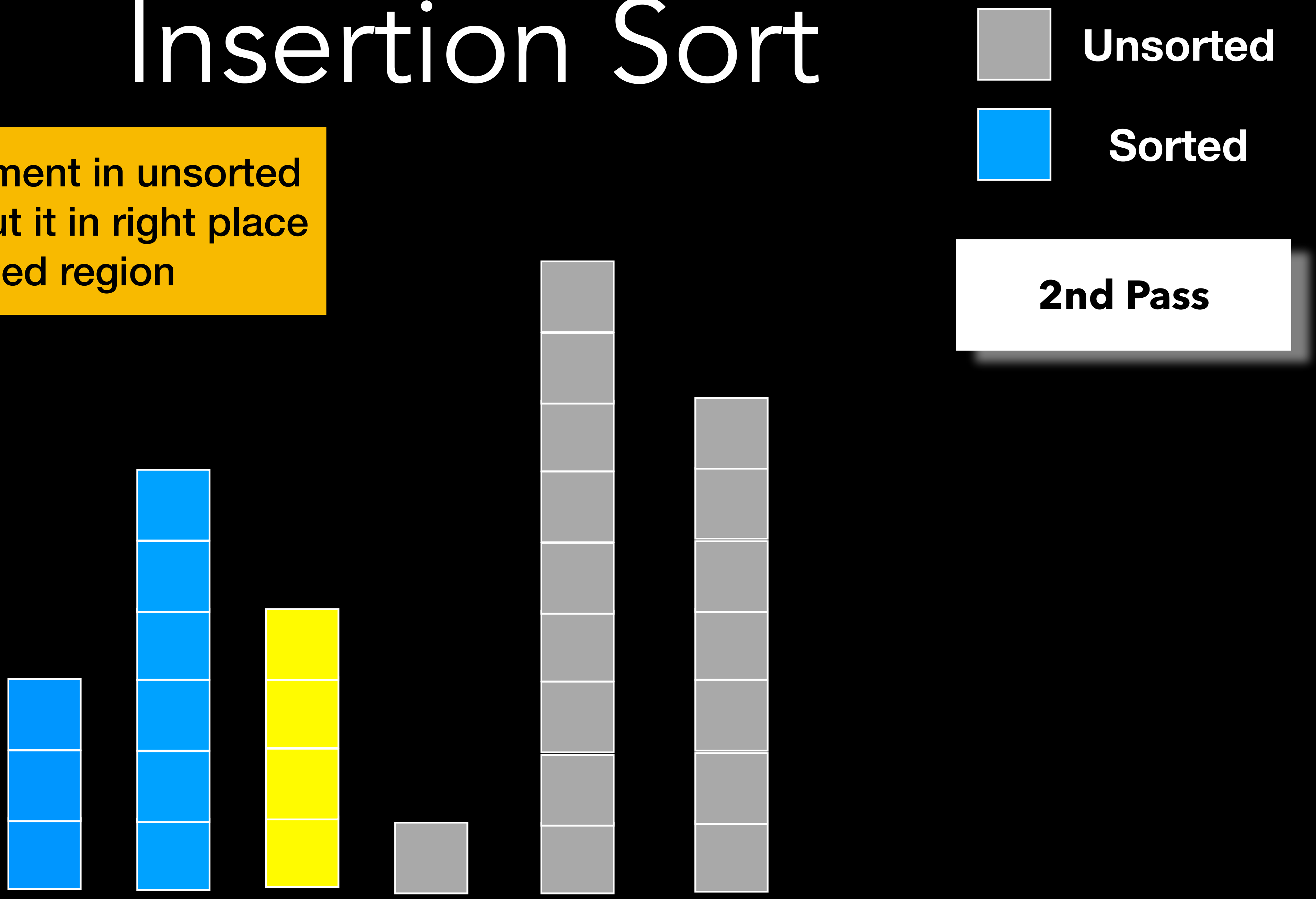
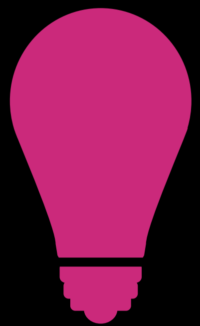


Insertion Sort



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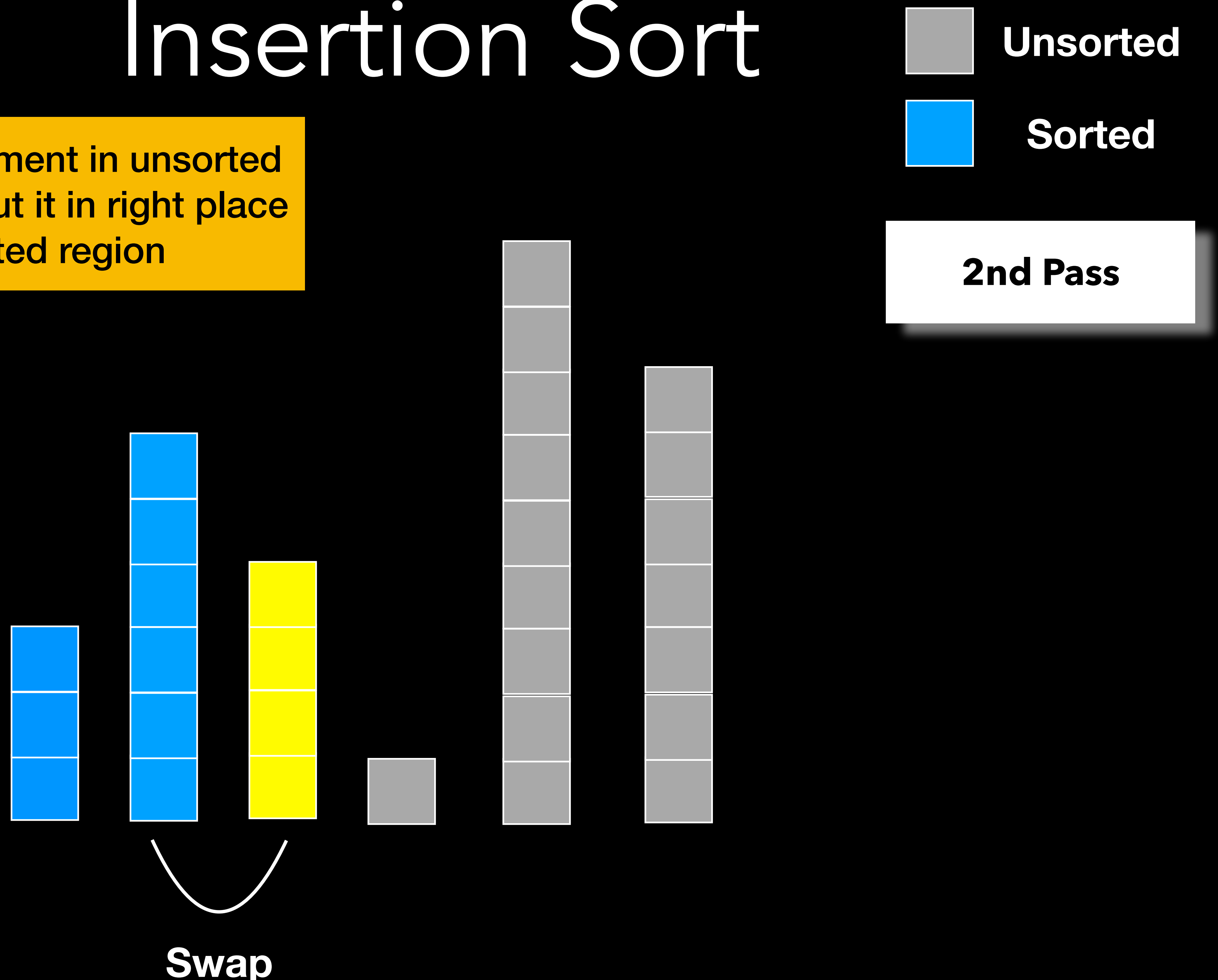


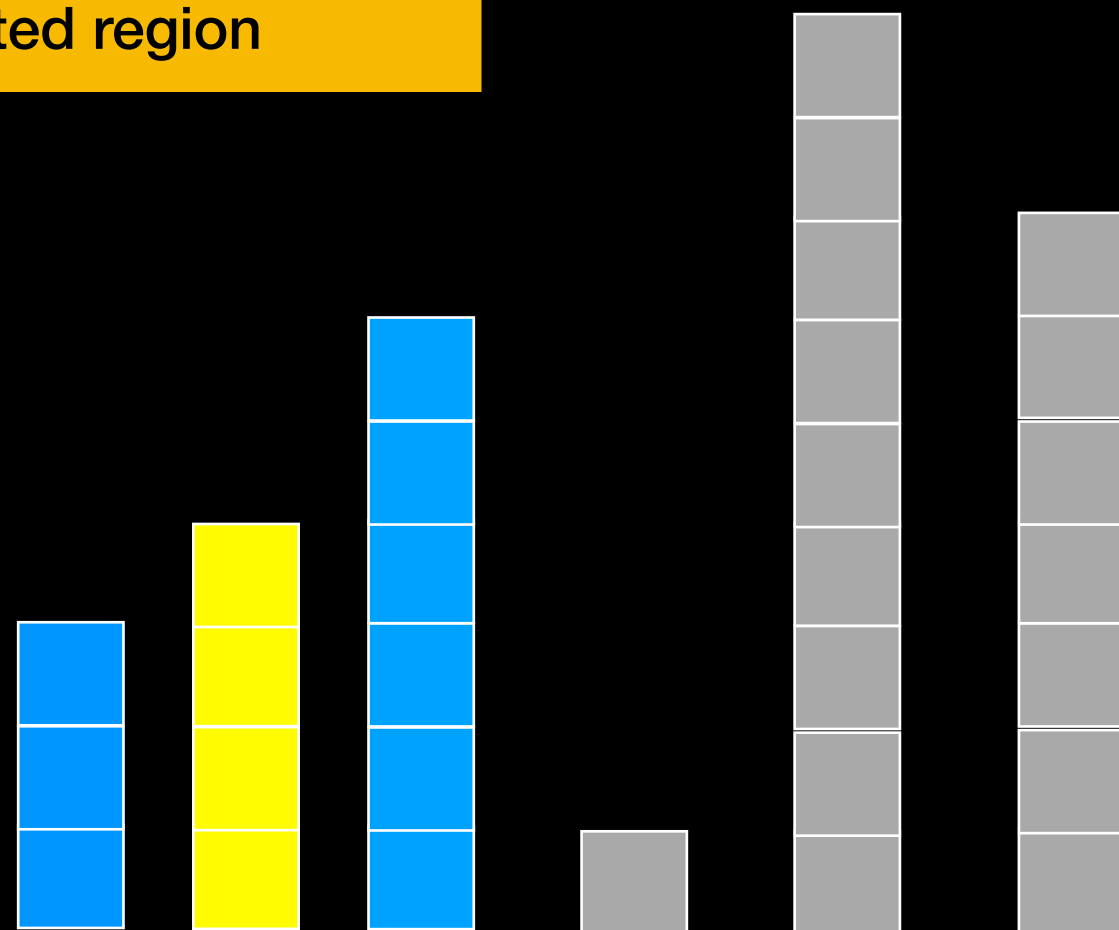
Insertion Sort

Unsorted

Sorted

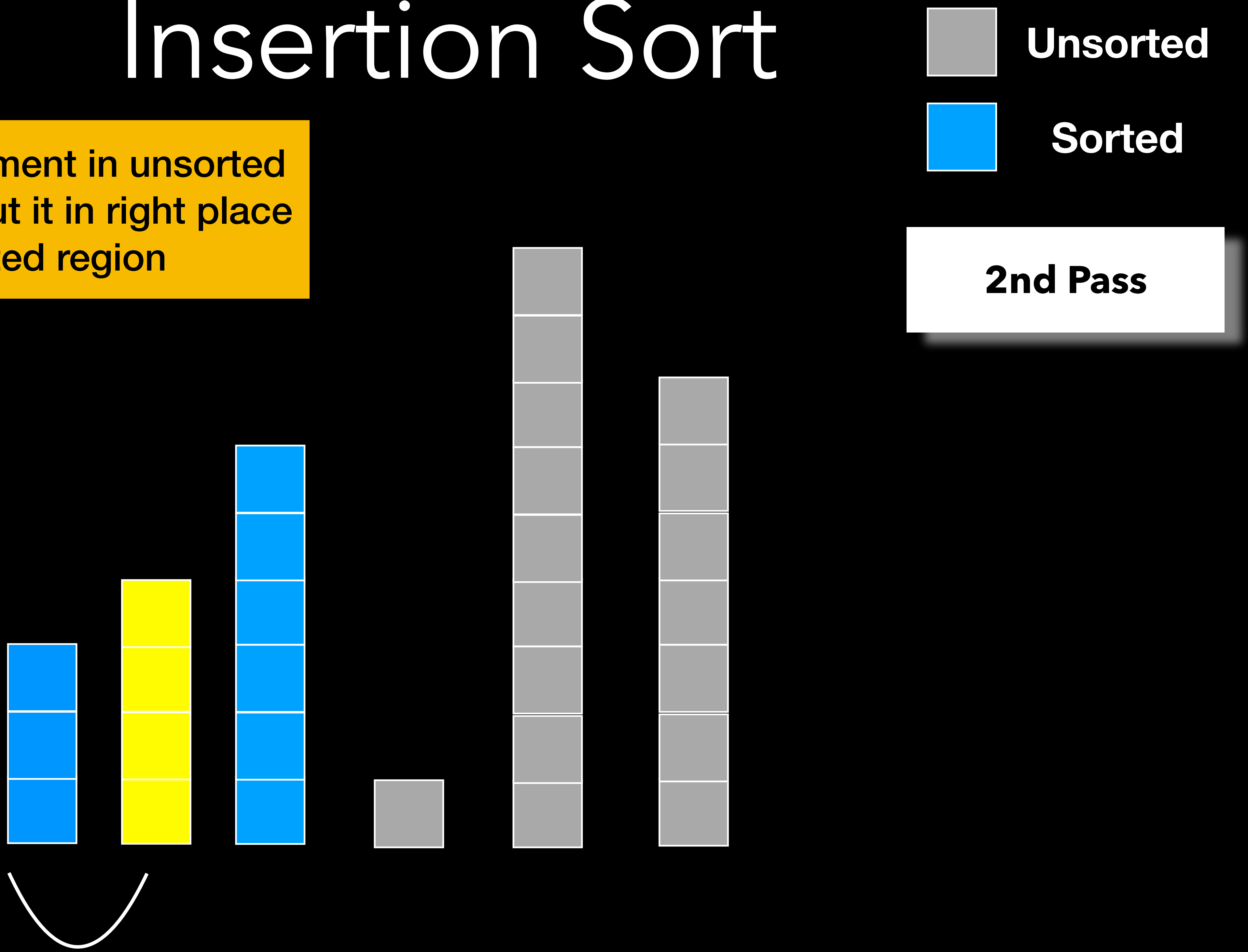
Pick first element in unsorted region and put it in right place in sorted region

2nd Pass



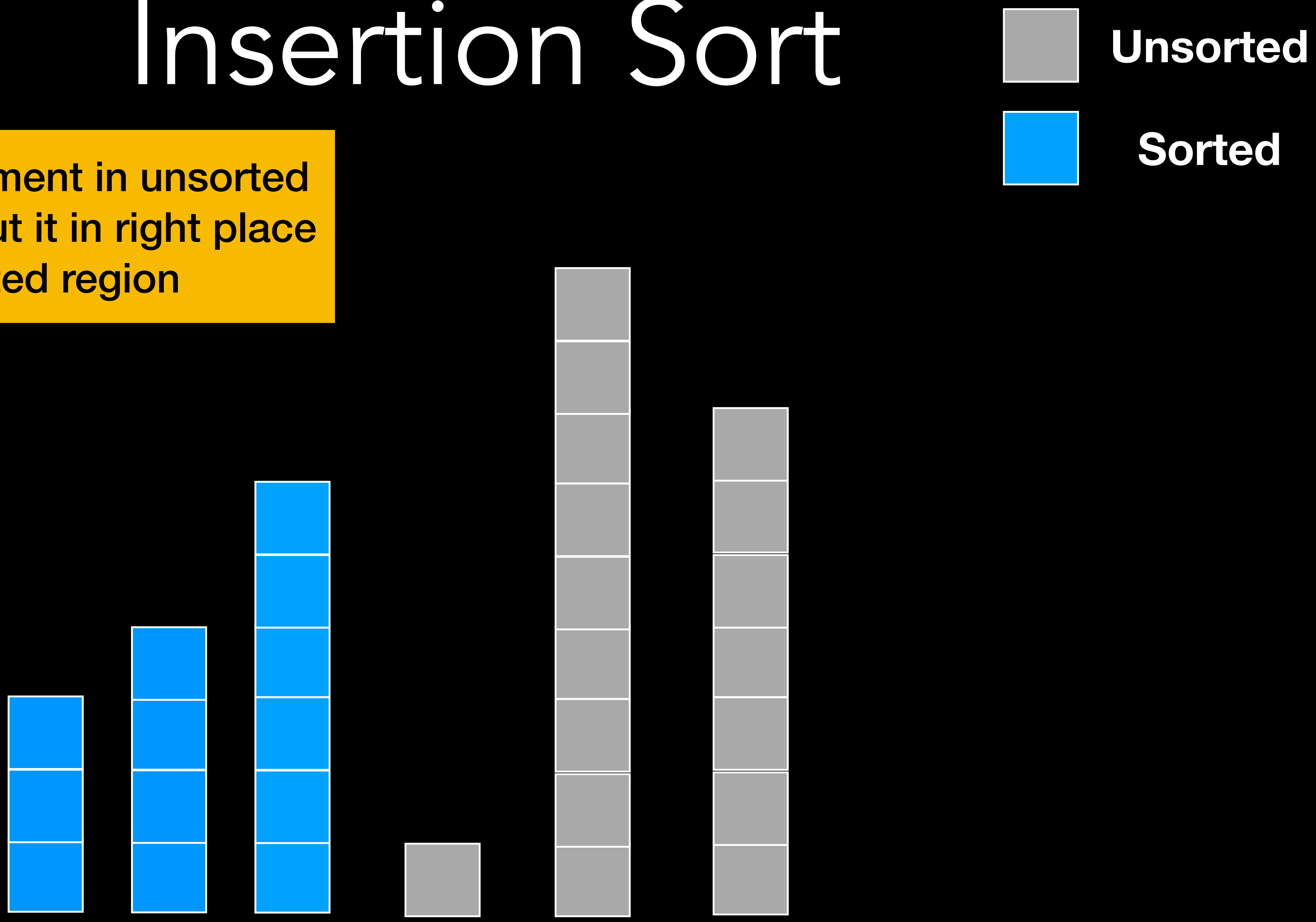
Insertion Sort

Pick first element in unsorted region and put it in right place in sorted region



Insertion Sort

Pick first element in unsorted region and put it in right place in sorted region



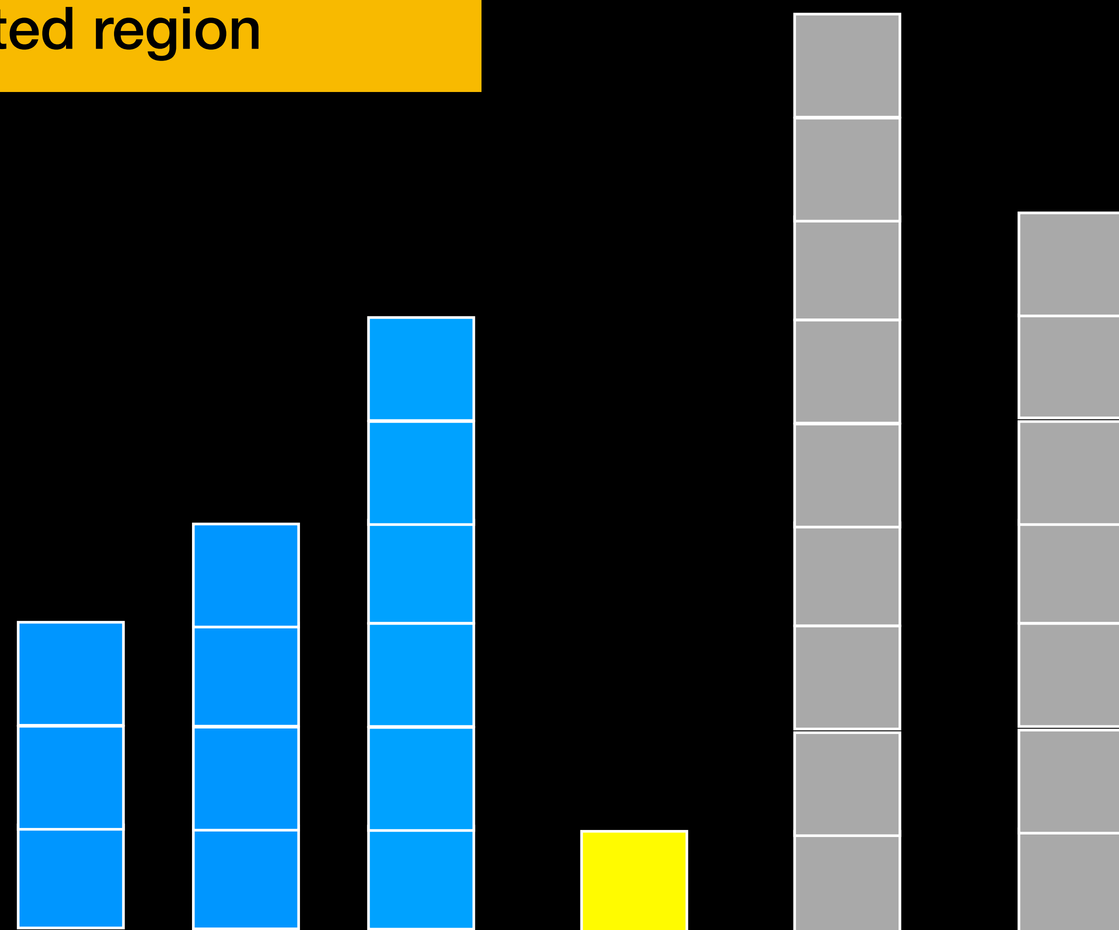
Insertion Sort

Unsorted

Sorted

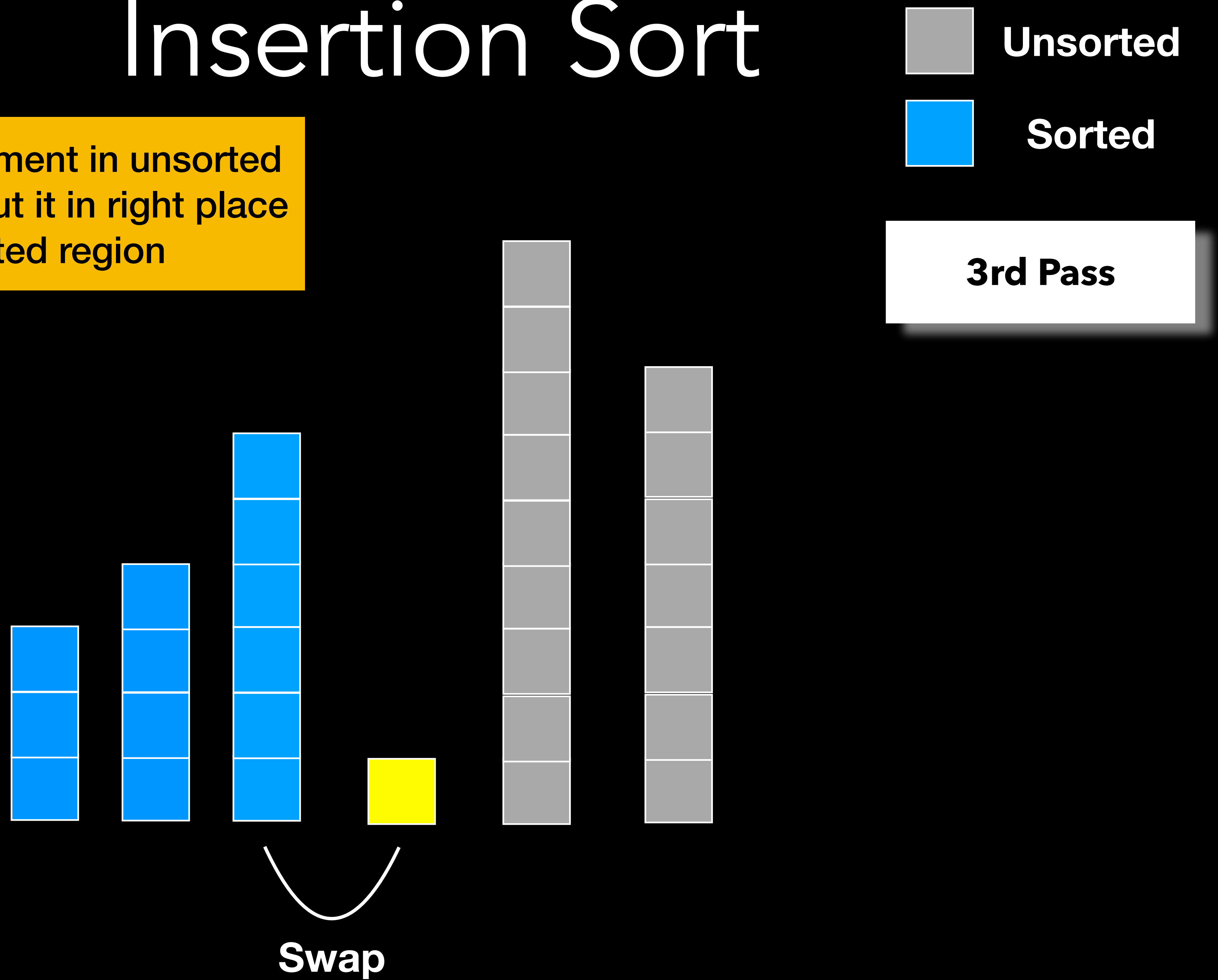
Pick first element in unsorted region and put it in right place in sorted region

3rd Pass



Insertion Sort

Pick first element in unsorted region and put it in right place in sorted region



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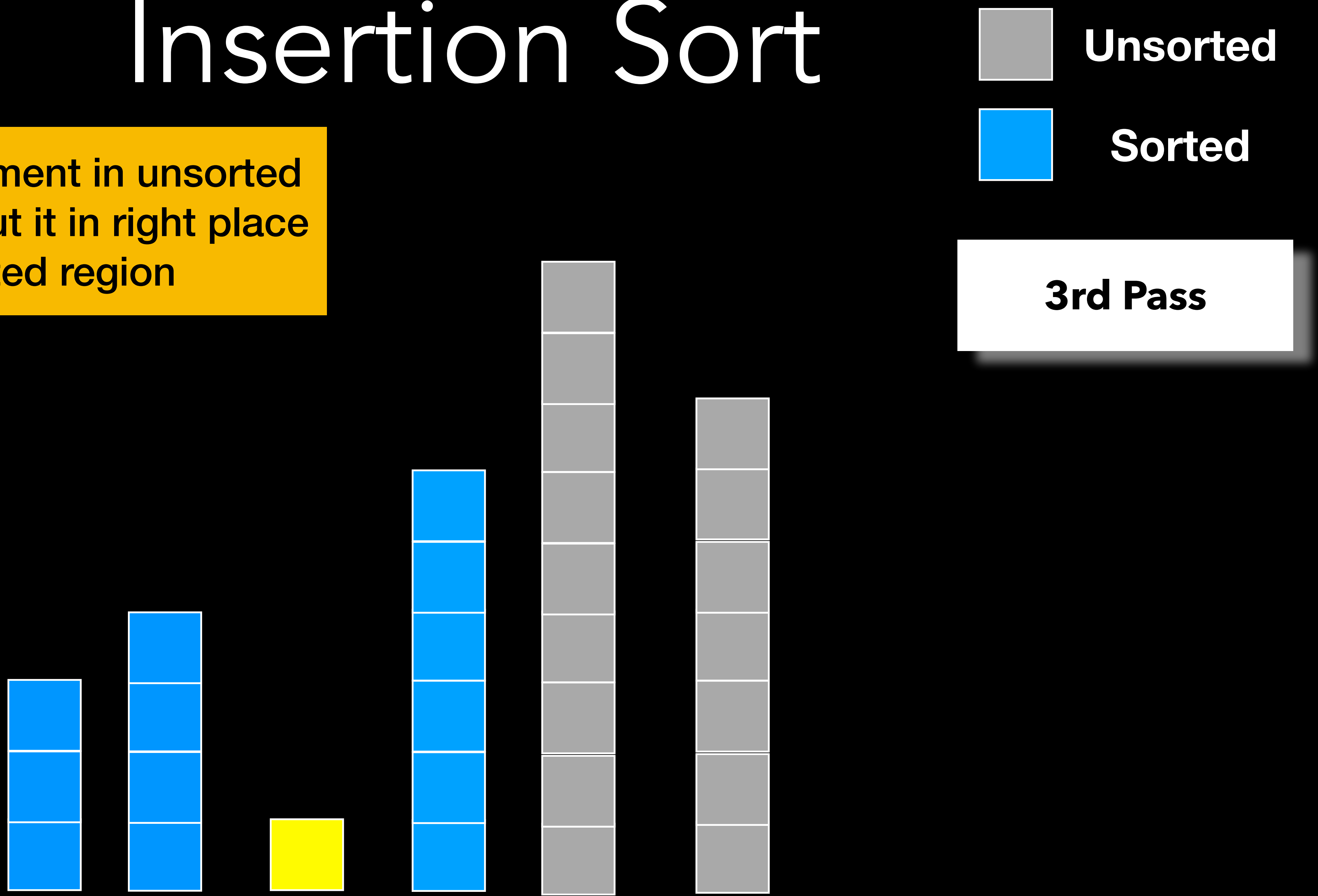

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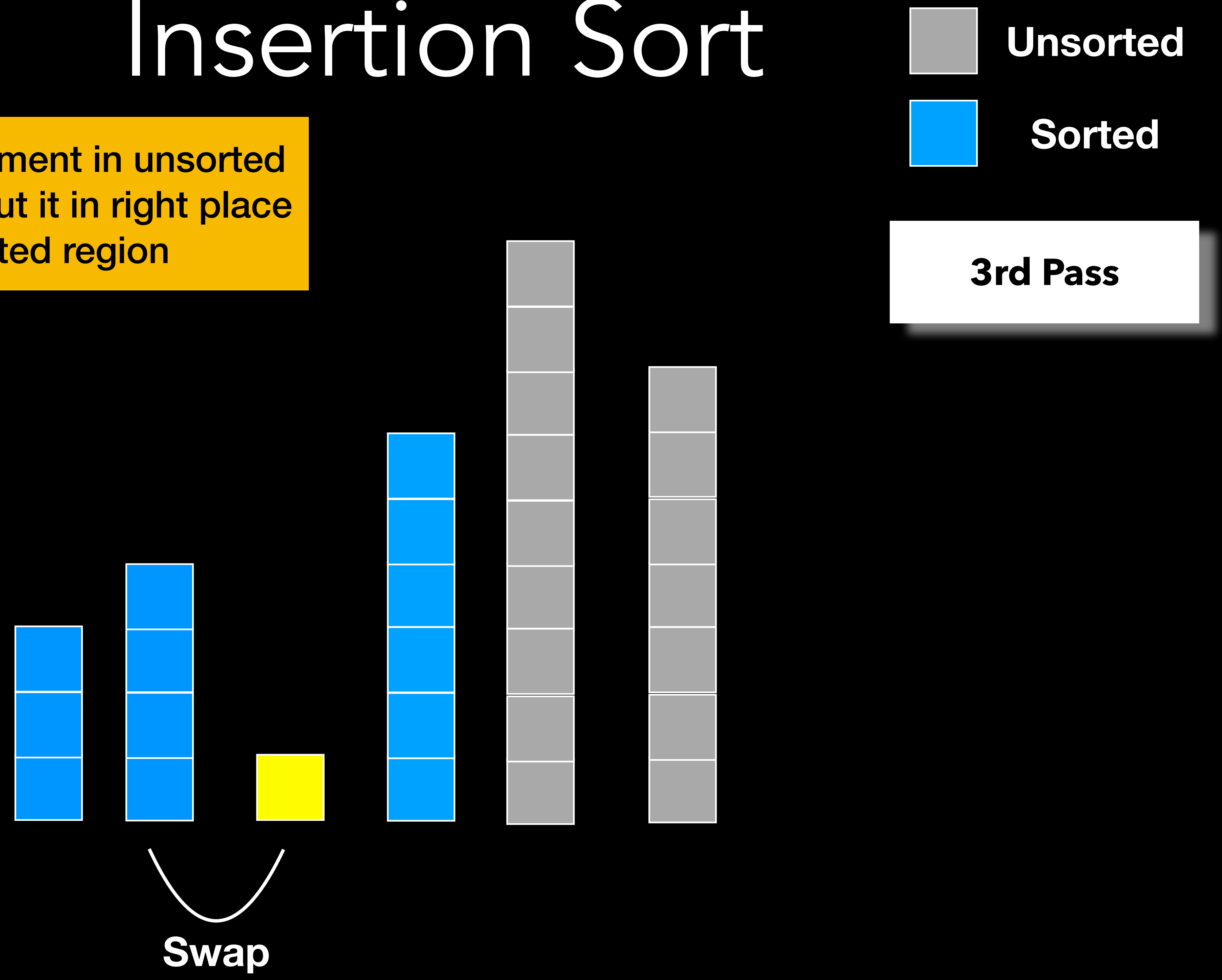

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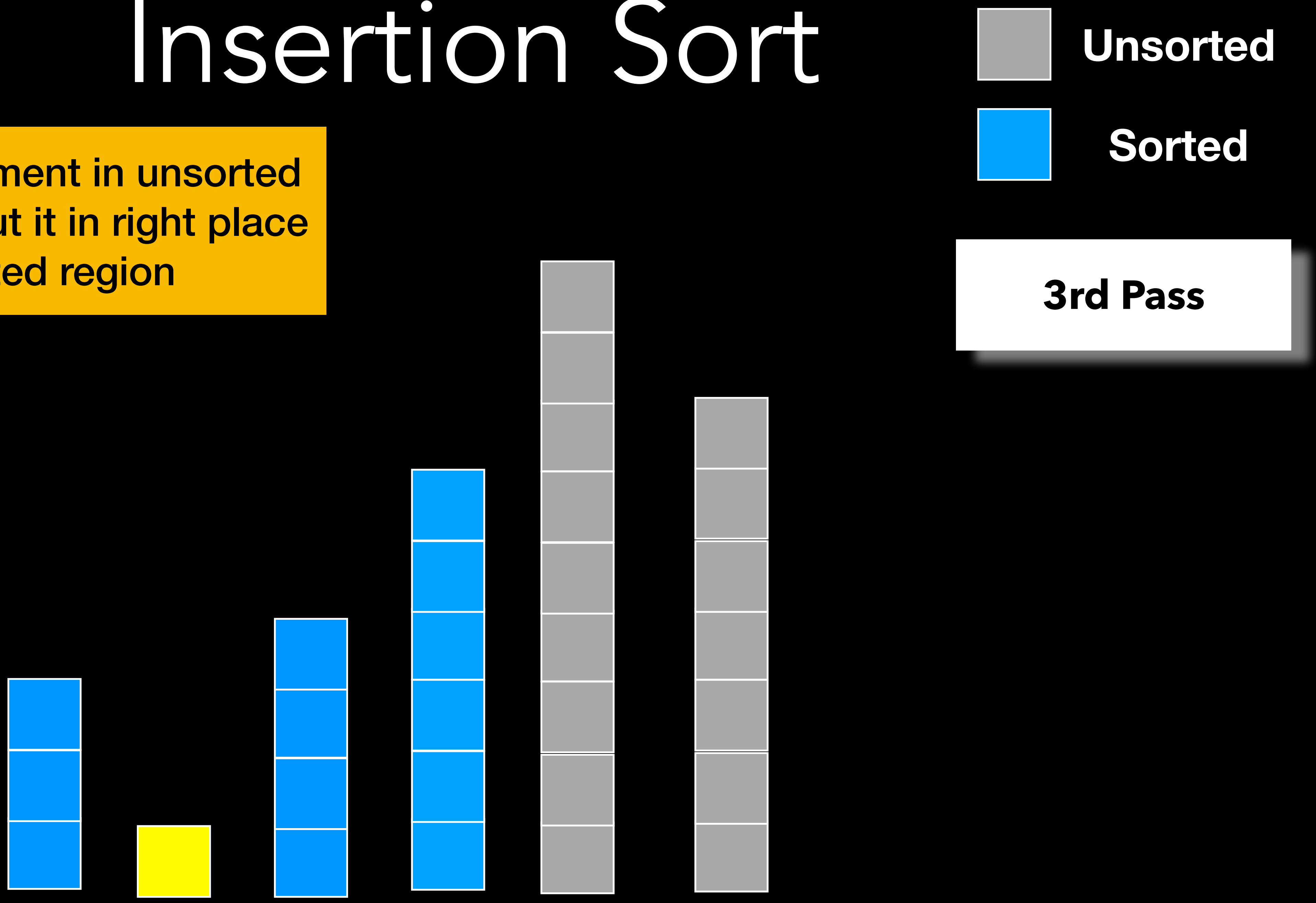


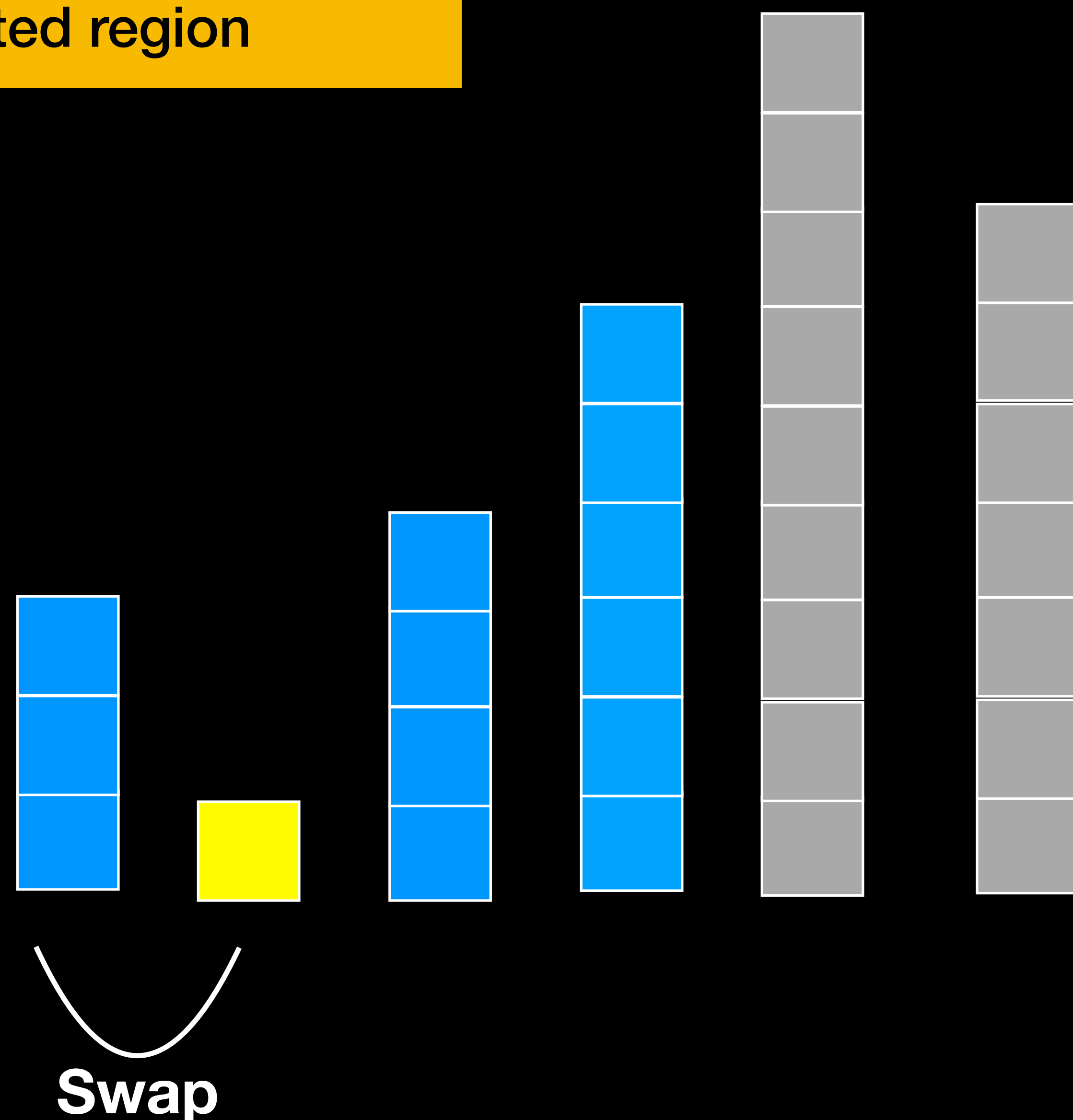
Insertion Sort

Unsorted

Sorted

Pick first element in unsorted region and put it in right place in sorted region

3rd Pass



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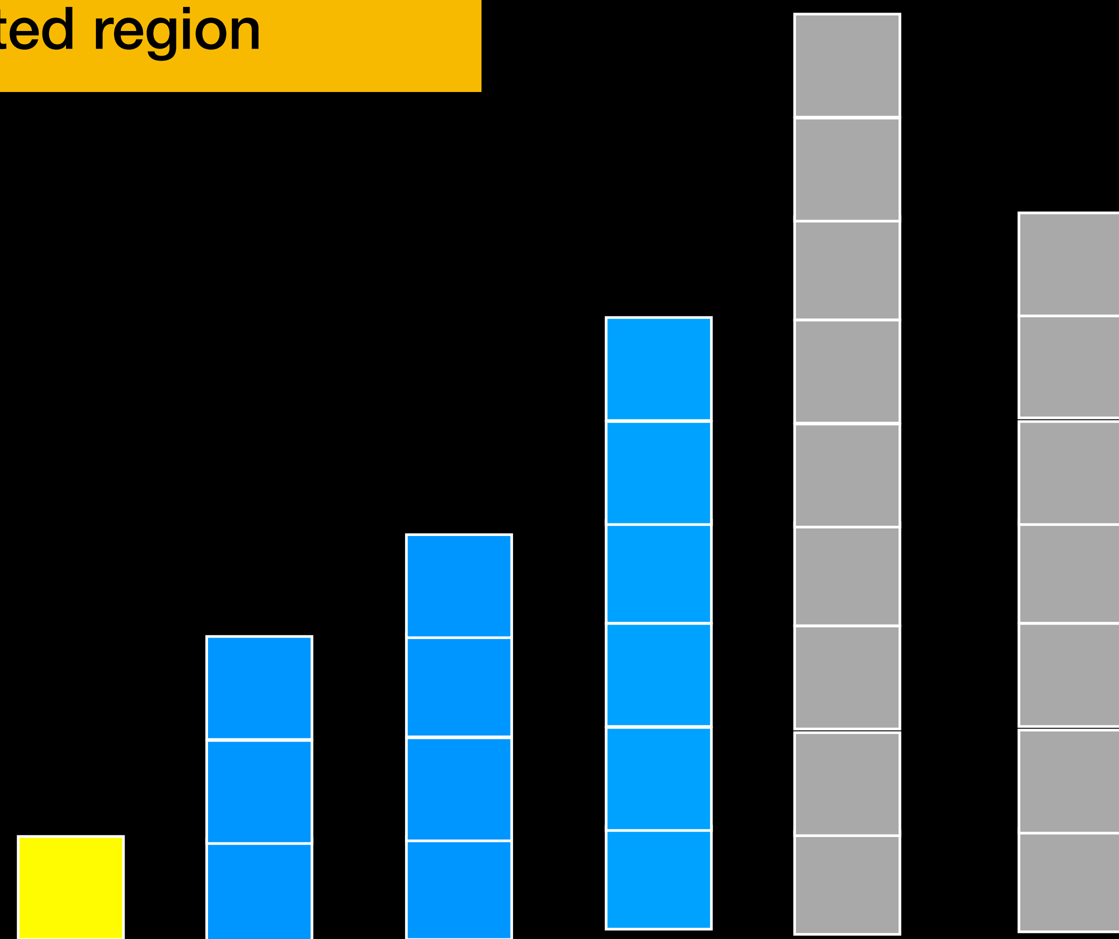
3rd Pass

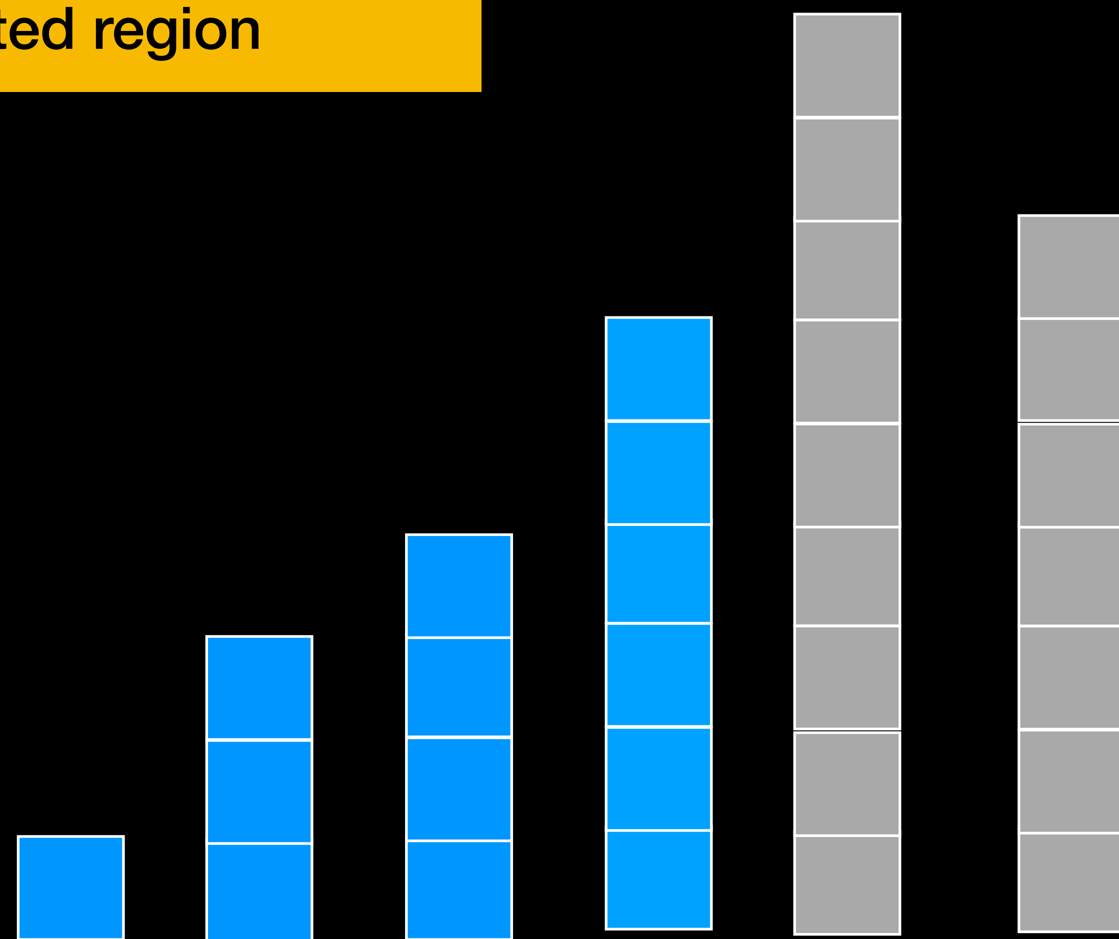


Insertion Sort

Unsorted

Sorted

Pick first element in unsorted region and put it in right place in sorted region



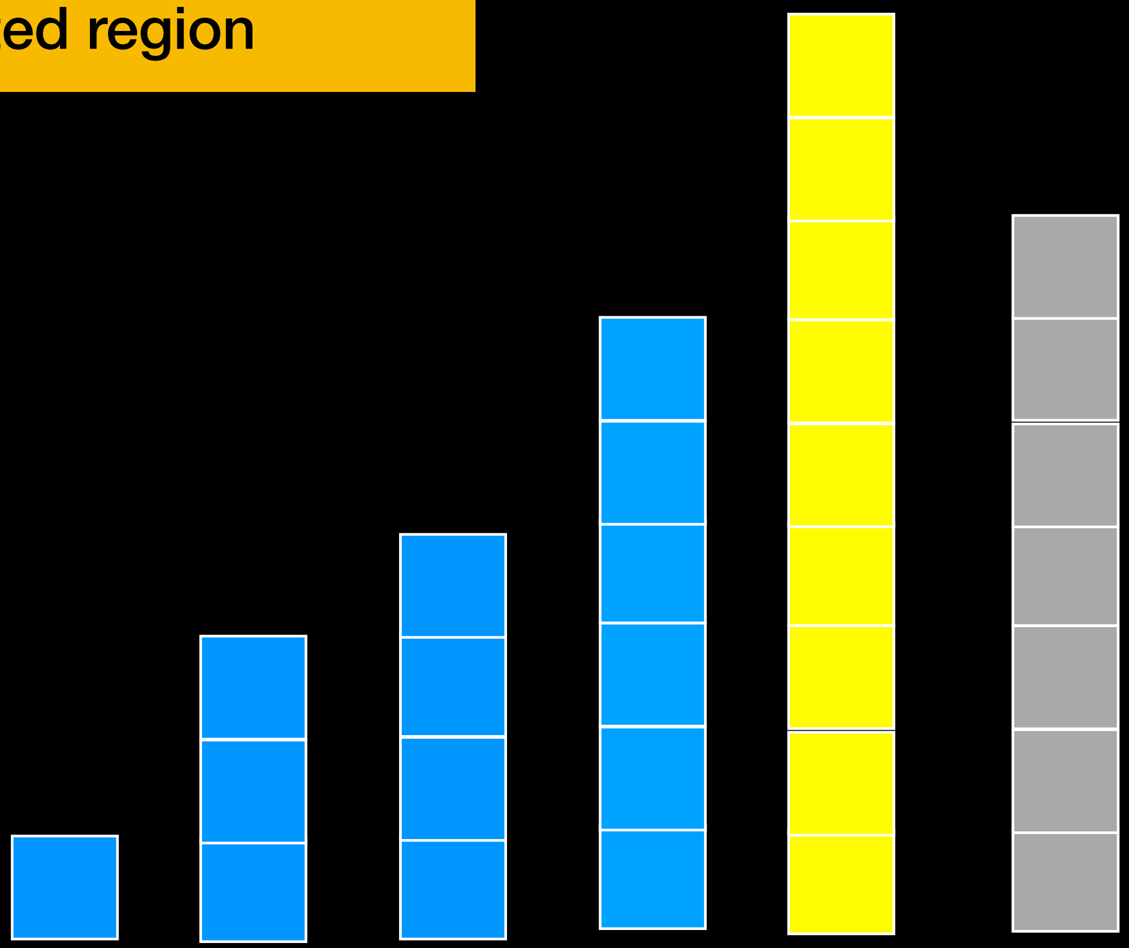
Insertion Sort

Pick first element in unsorted region and put it in right place in sorted region

Unsorted

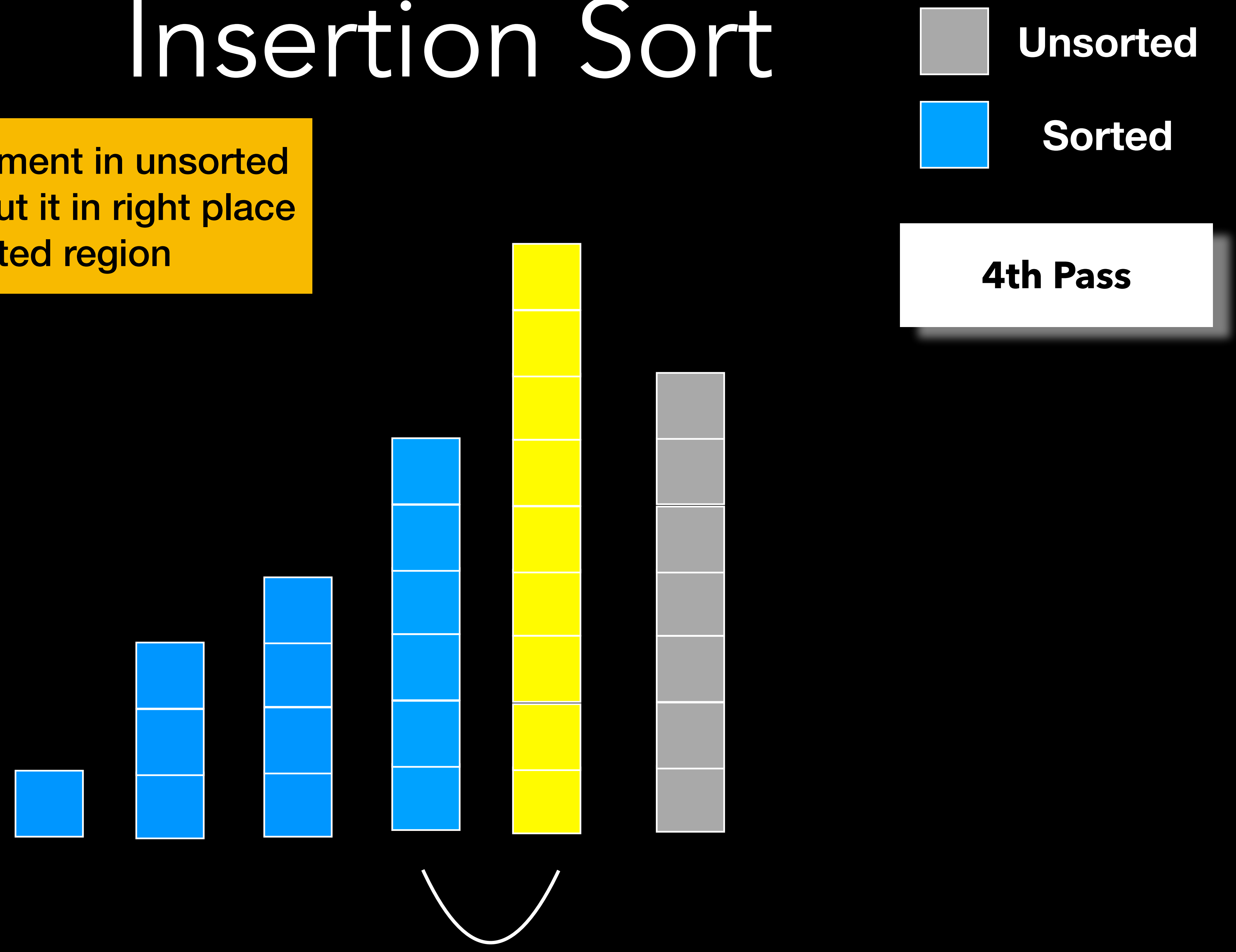
Sorted

4th Pass



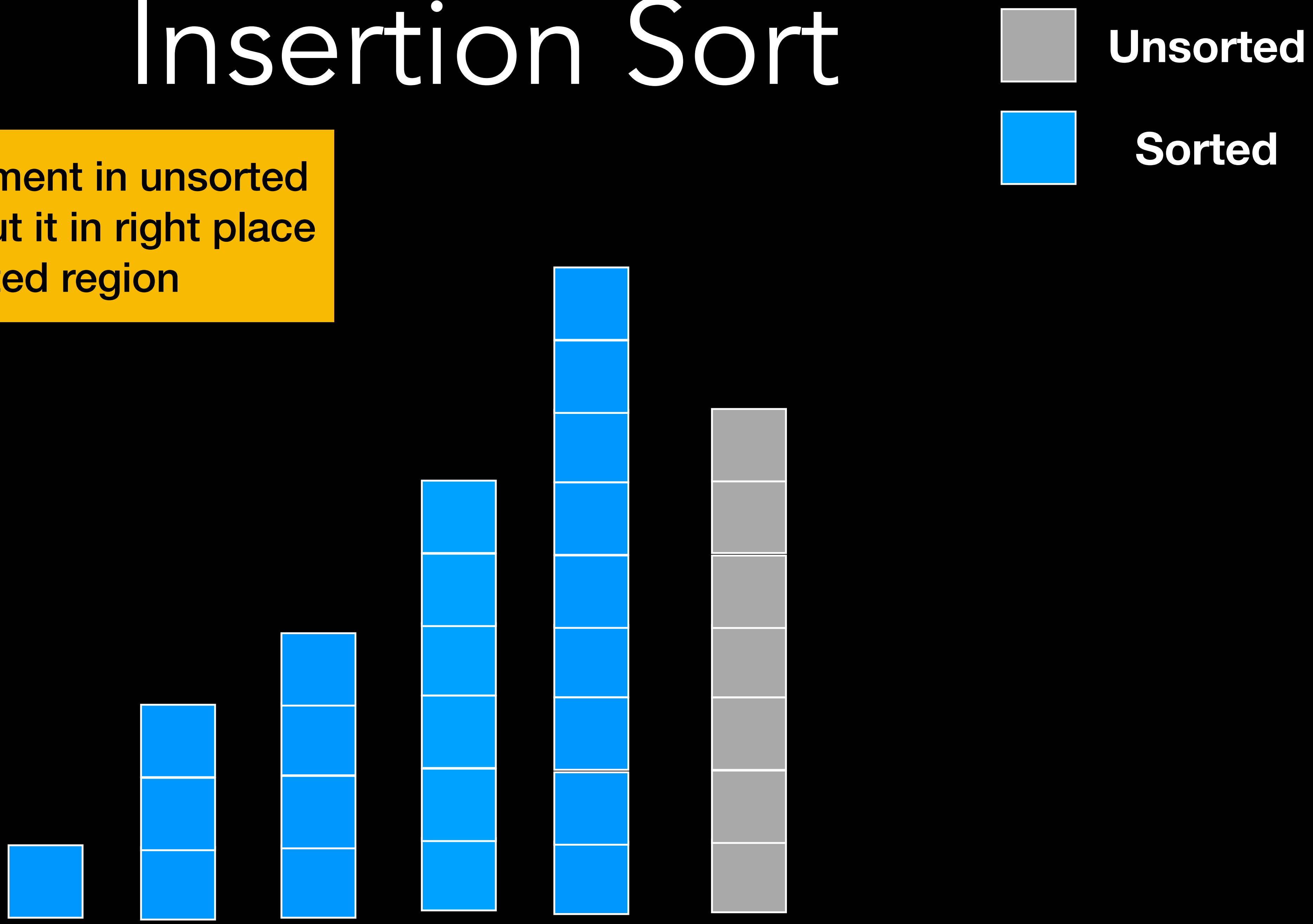
Insertion Sort

Pick first element in unsorted region and put it in right place in sorted region



Insertion Sort

Pick first element in unsorted region and put it in right place in sorted region



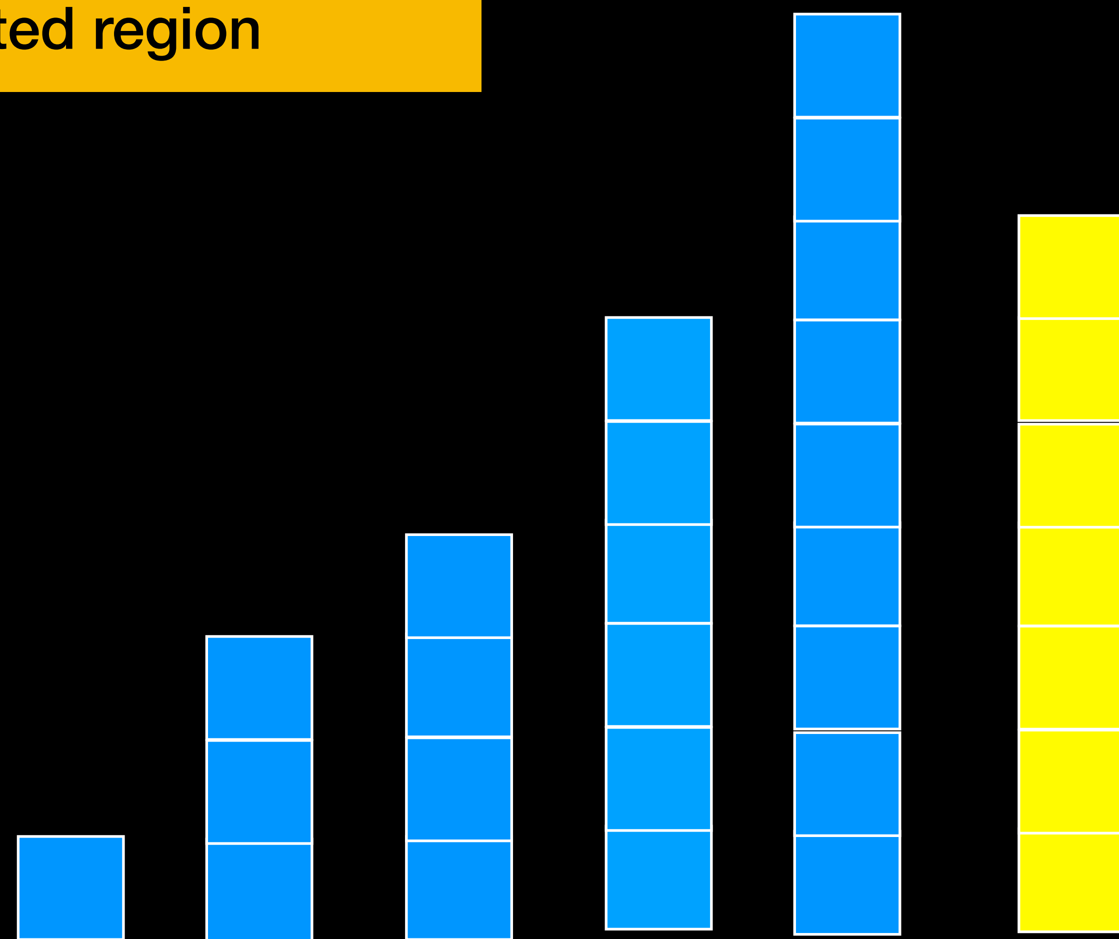
Insertion Sort

Unsorted

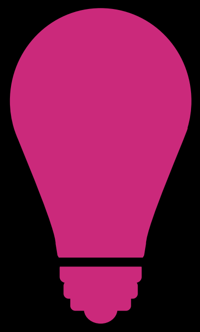
Sorted

Pick first element in unsorted region and put it in right place in sorted region

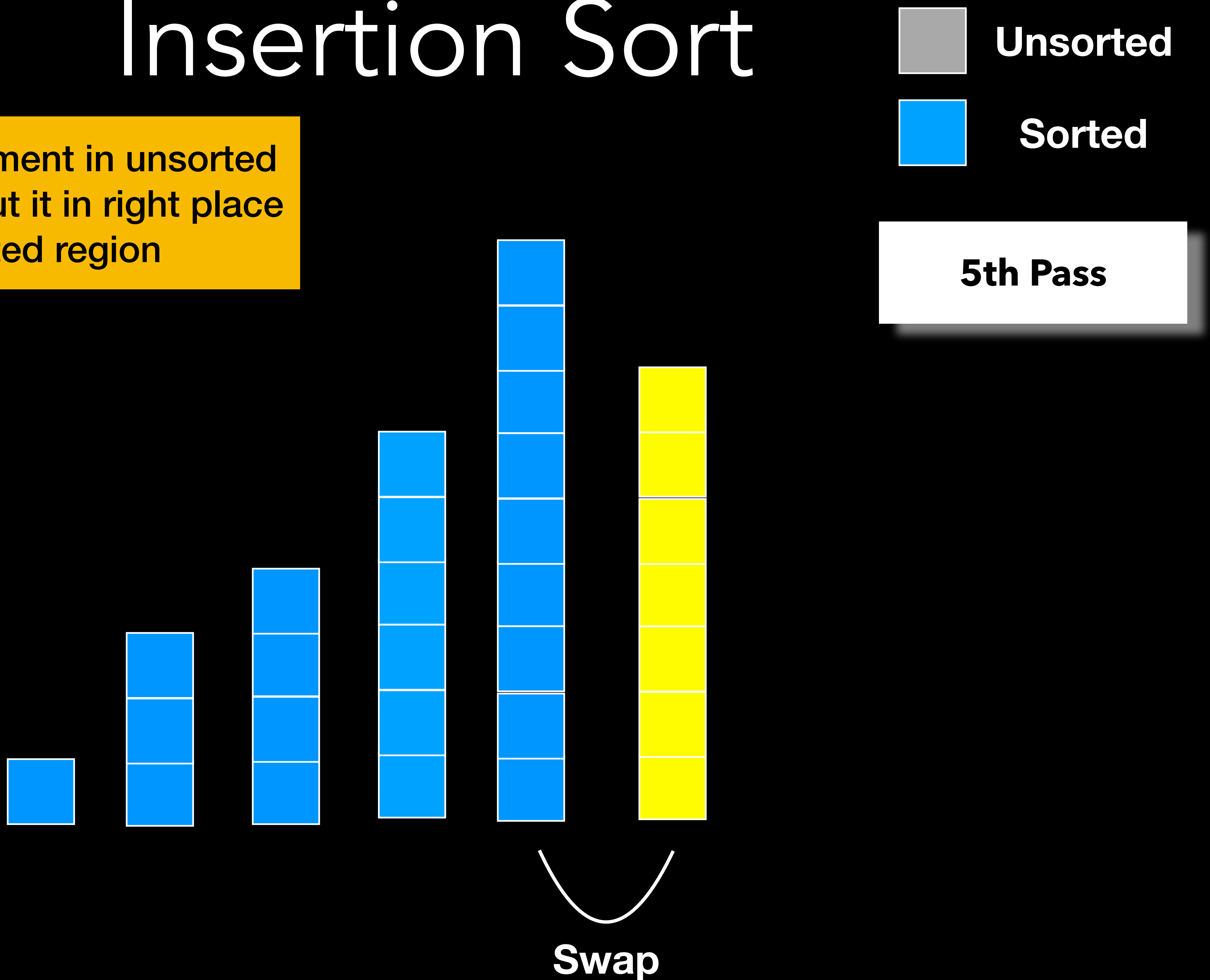
5th Pass



Insertion Sort



Pick first element in unsorted region and put it in right place in sorted region



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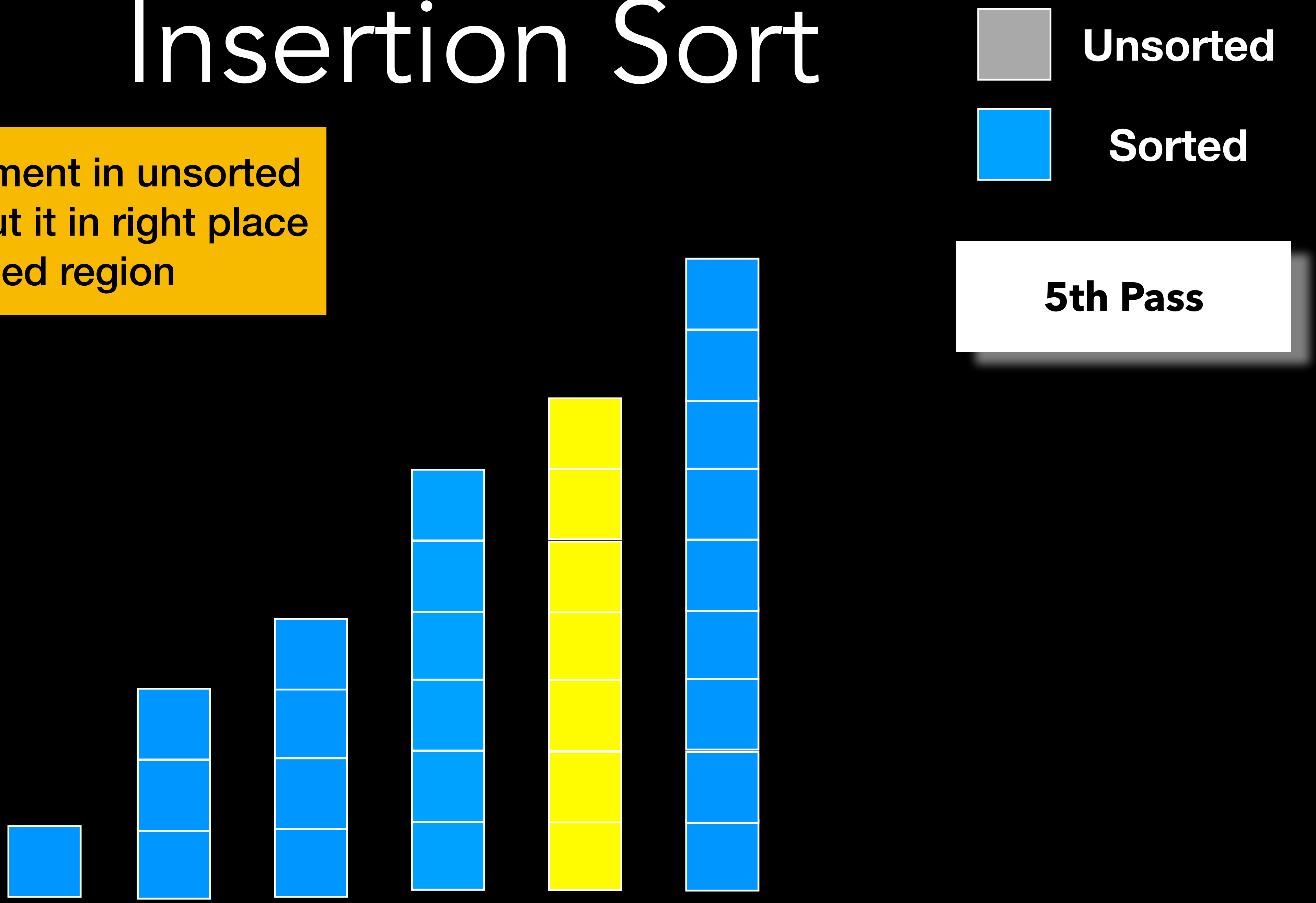


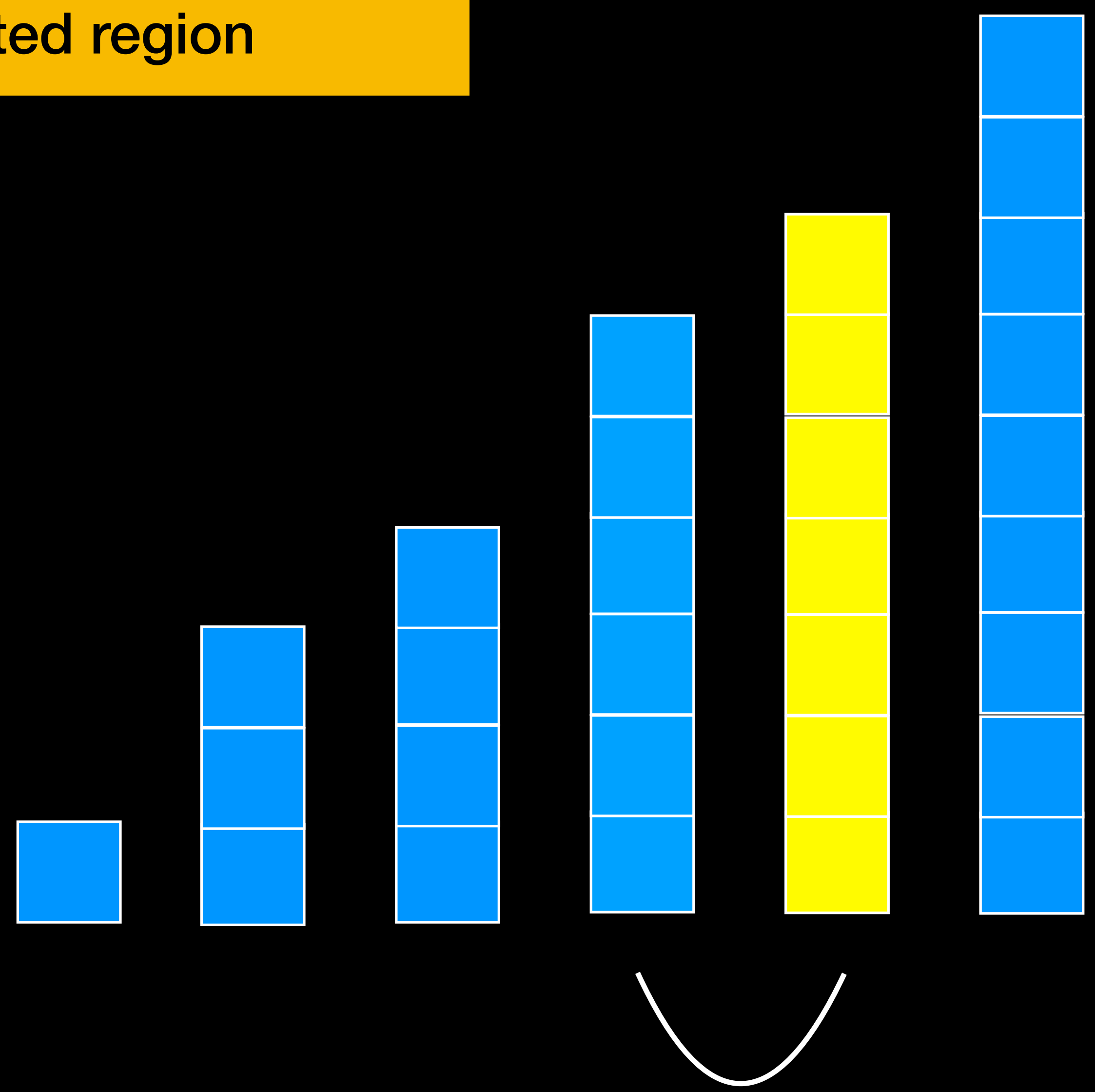
Insertion Sort

Unsorted

Sorted

Pick first element in unsorted region and put it in right place in sorted region

5th Pass



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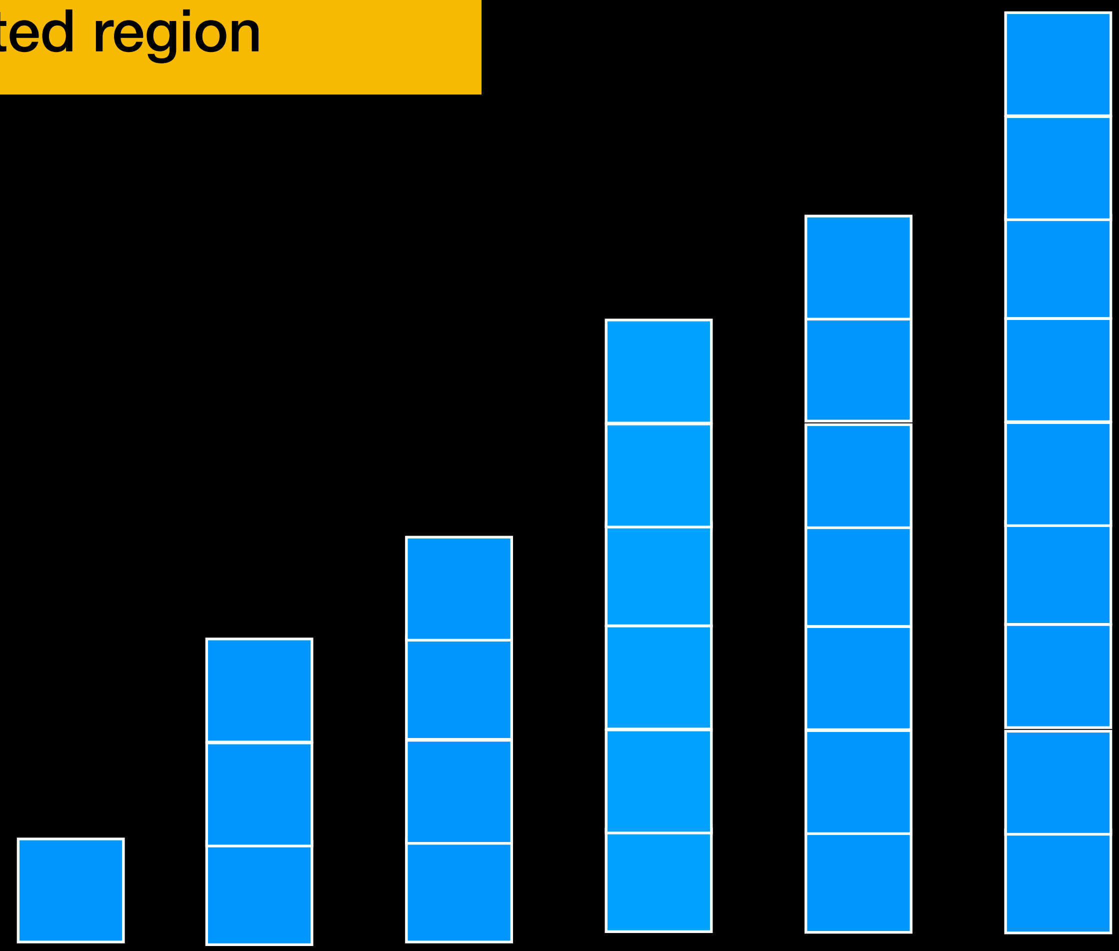


Insertion Sort Analysis

How much work?

First pass: **1** comparison and at most **1** swap

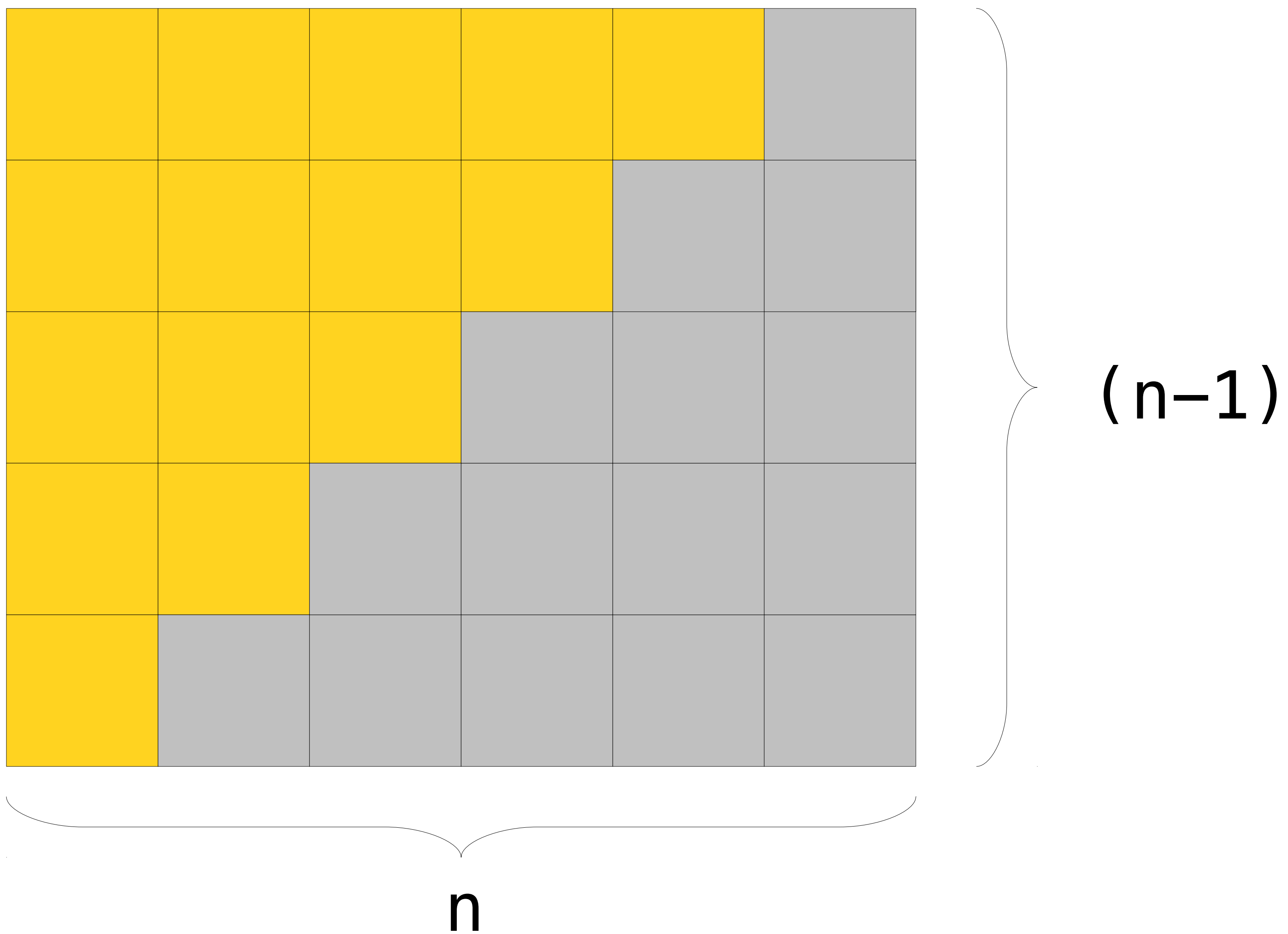
Second pass: at most **2** comparisons and at most **2** swaps

Third pass: at most **3** comparisons and at most **3** swaps

. . .

Total work: **1 + 2 + 3 + . . . + (n-1)**

$$1 + 2 + \ldots (n-2) + (n-1) = n(n-1)/2$$



Insertion Sort Analysis

$T(n) = n(n-1) / 2$ comparisons $+ n(n-1) / 2$ swaps $= O(\ )$?

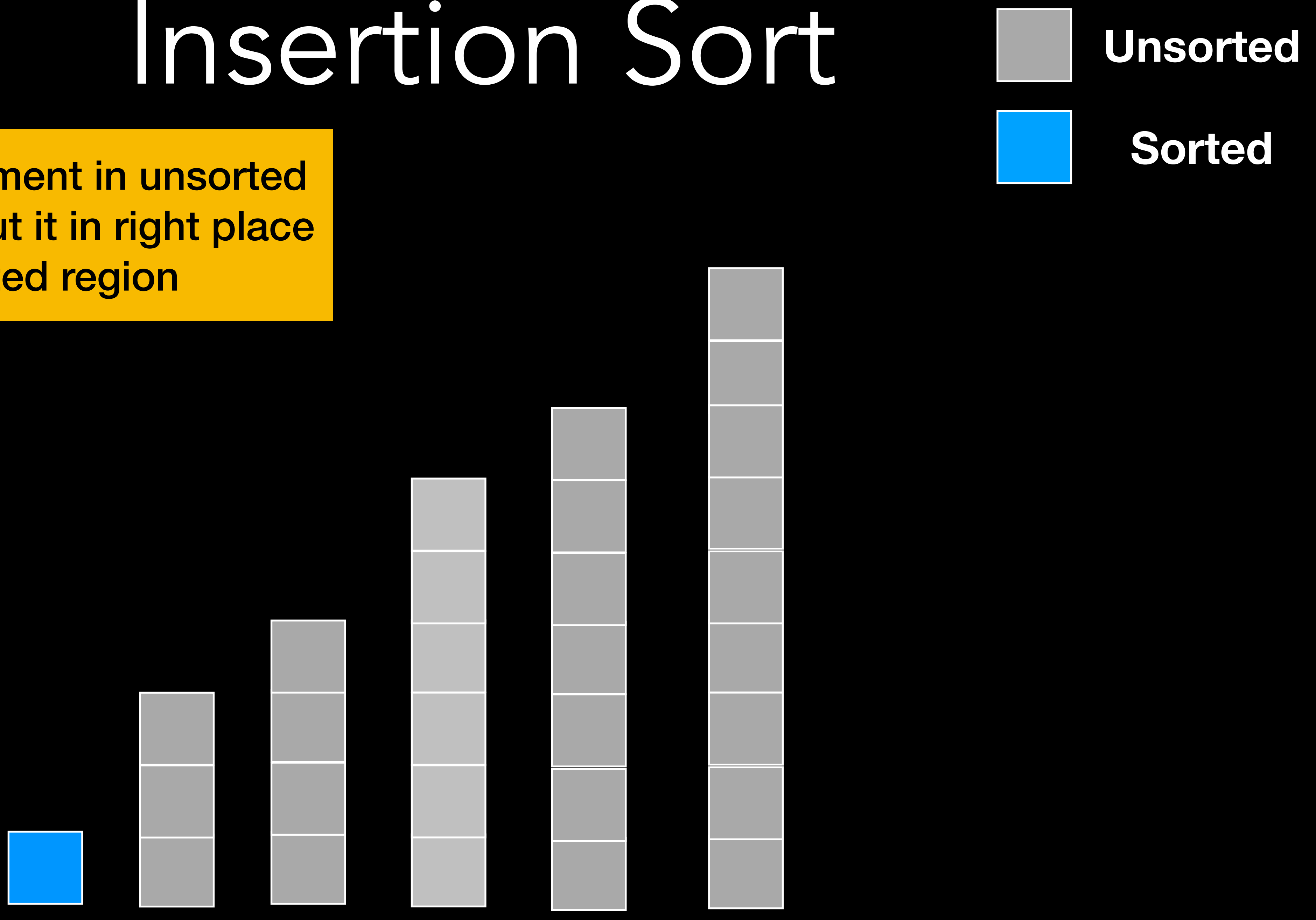
$T(n) = 2((n^2-n) / 2) = O(\ )$?

$T(n) = n^2-n = O(\mathbf{n^2})$

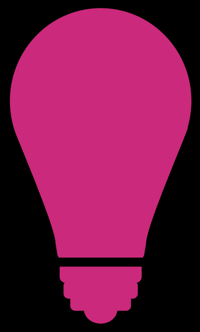
Insertion Sort run time is $\mathbf{O(n^2)}$

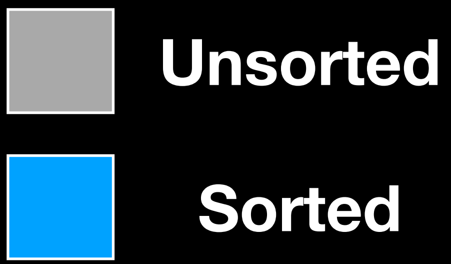
Insertion Sort

Pick first element in unsorted region and put it in right place in sorted region

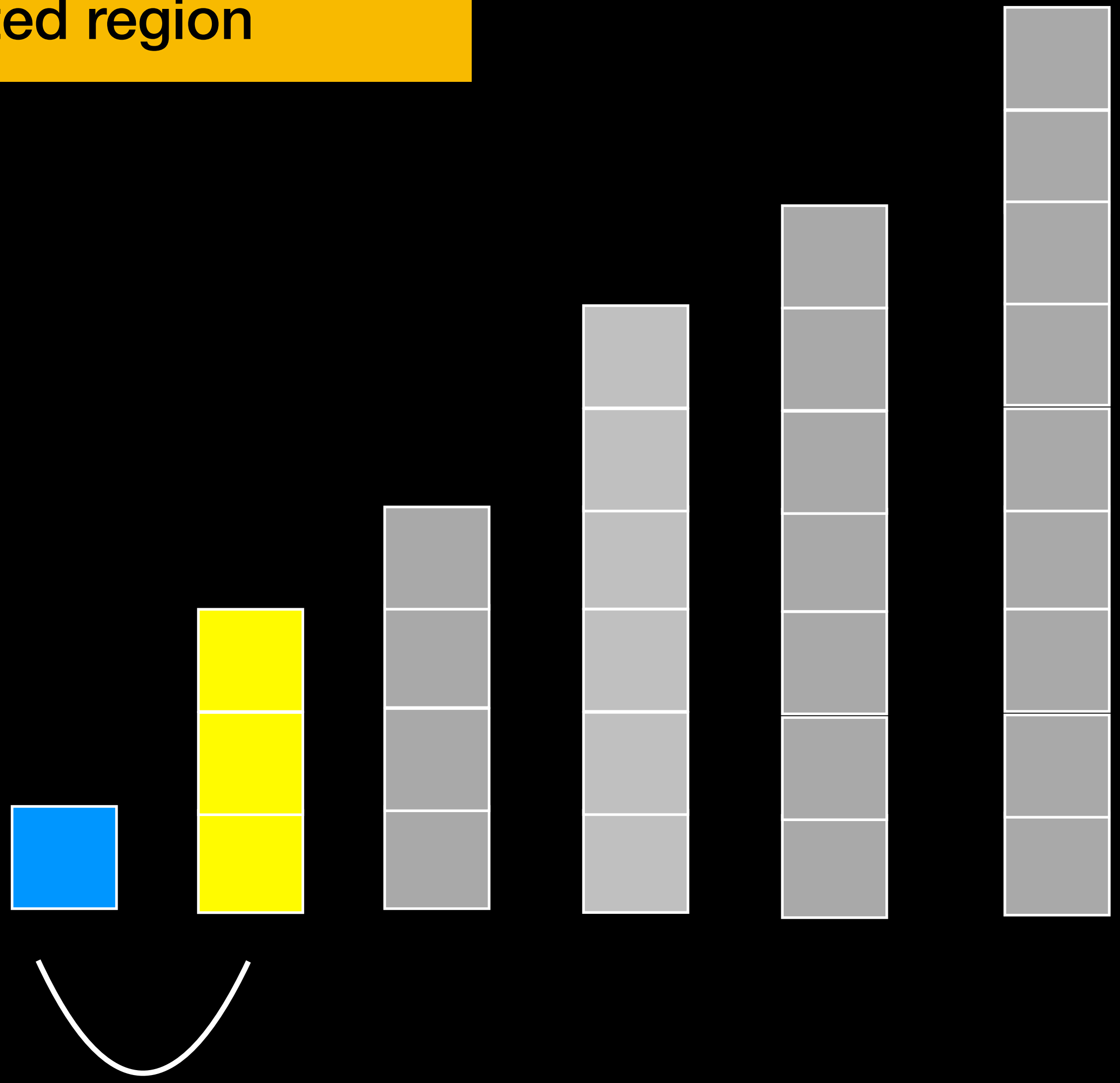


Insertion Sort

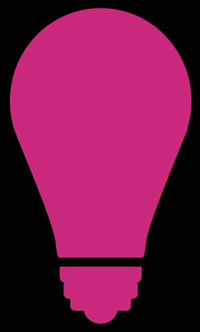




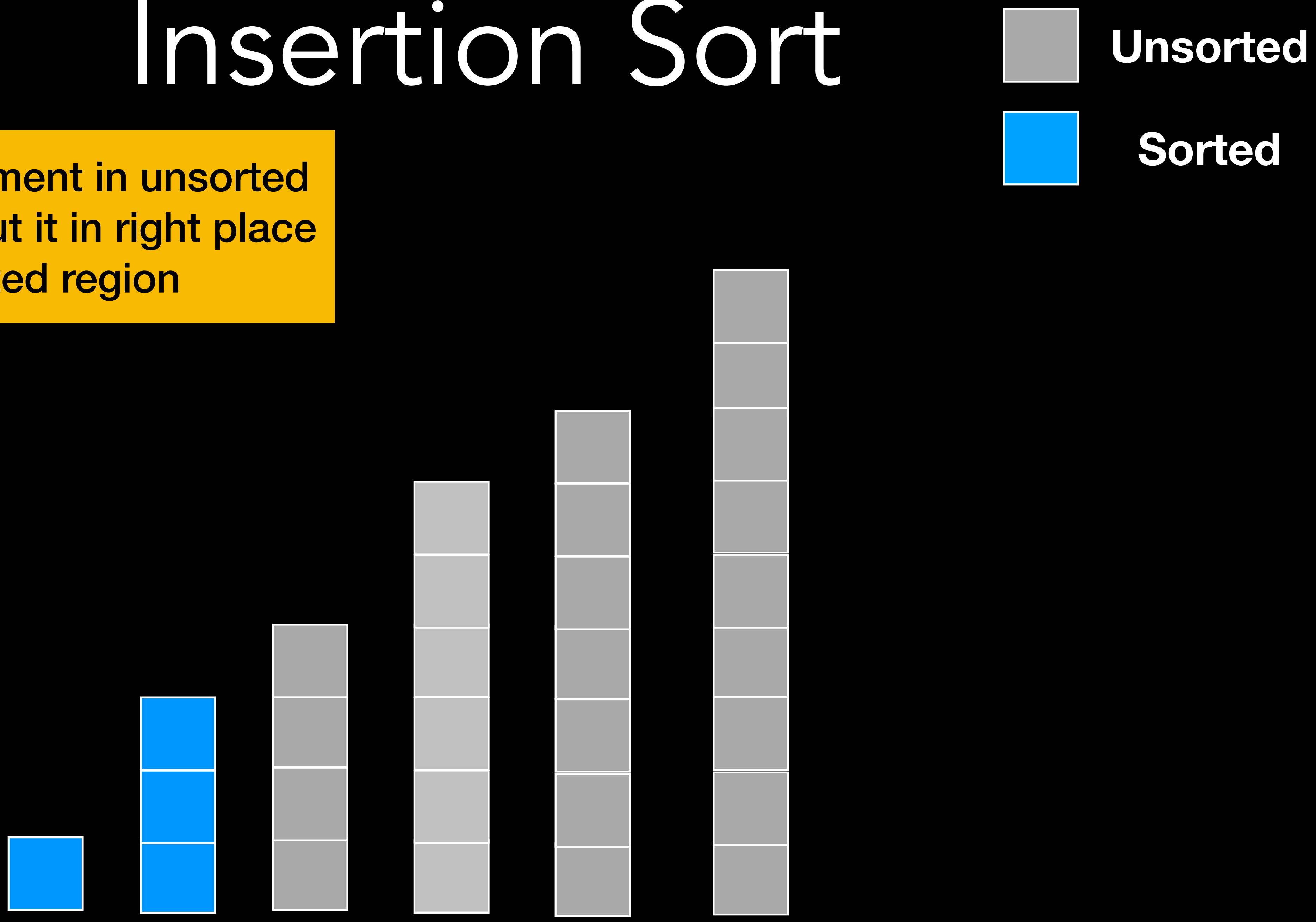
Pick first element in unsorted region and put it in right place in sorted region



Insertion Sort



Pick first element in unsorted region and put it in right place in sorted region

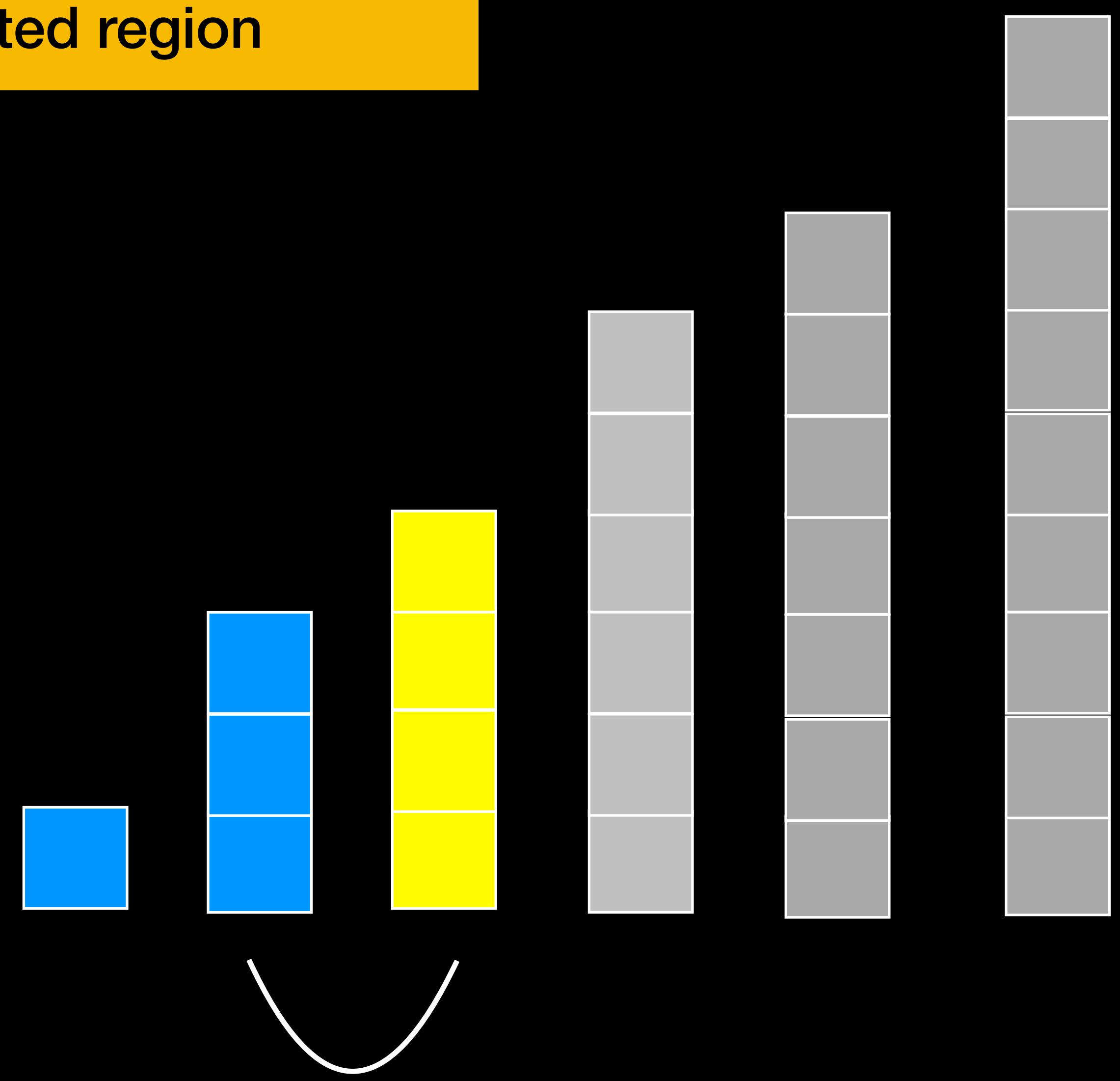


Insertion Sort

Unsorted

Sorted

Pick first element in unsorted region and put it in right place in sorted region

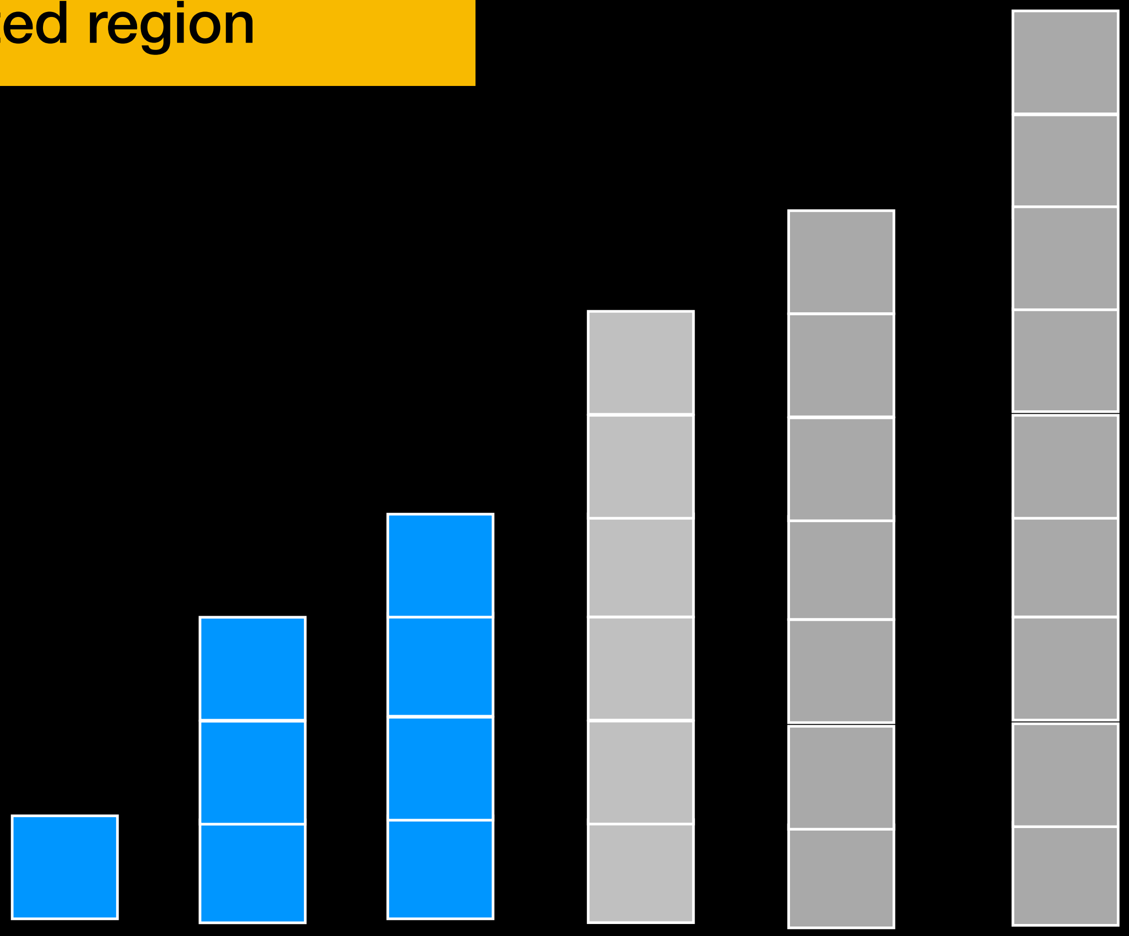


Insertion Sort

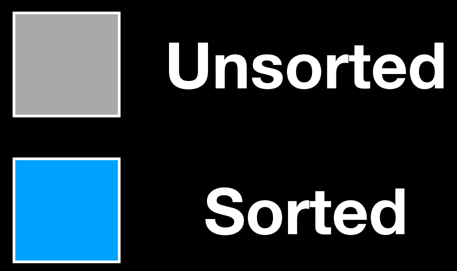
Unsorted

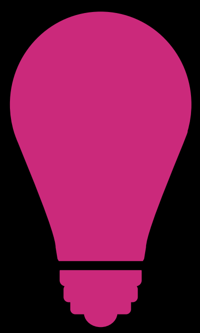
Sorted

Pick first element in unsorted region and put it in right place in sorted region

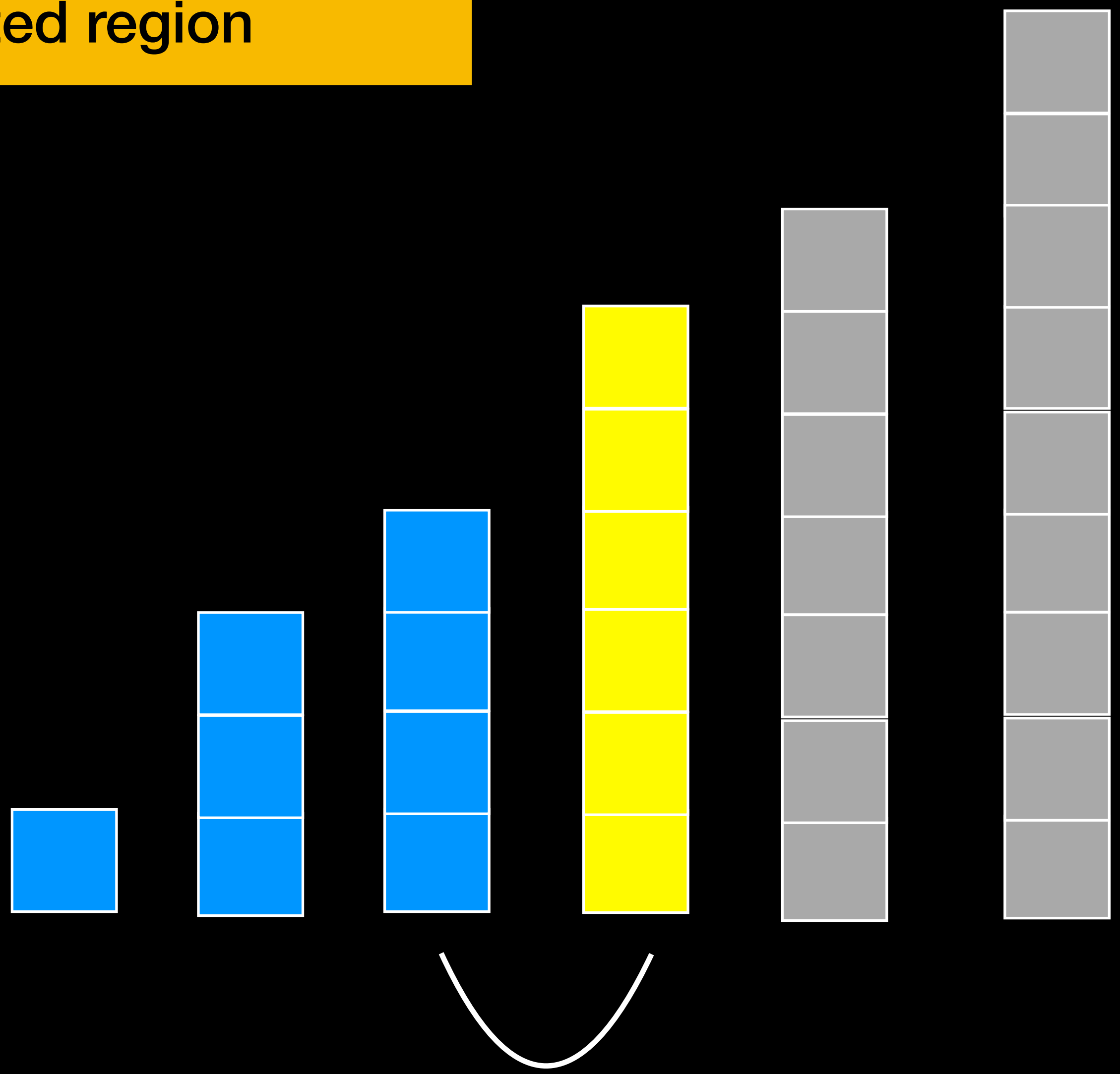


Insertion Sort





Pick first element in unsorted region and put it in right place in sorted region

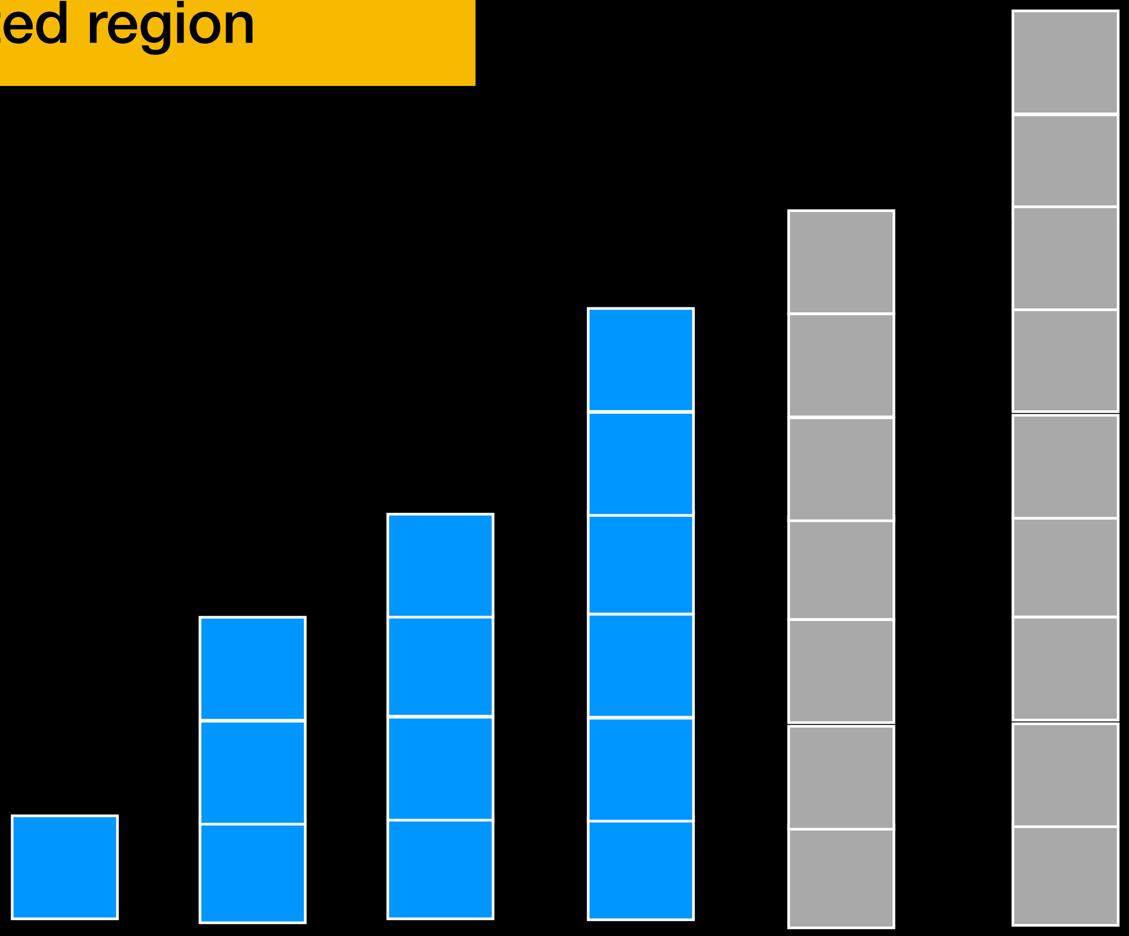


Insertion Sort

Unsorted

Sorted

Pick first element in unsorted region and put it in right place in sorted region

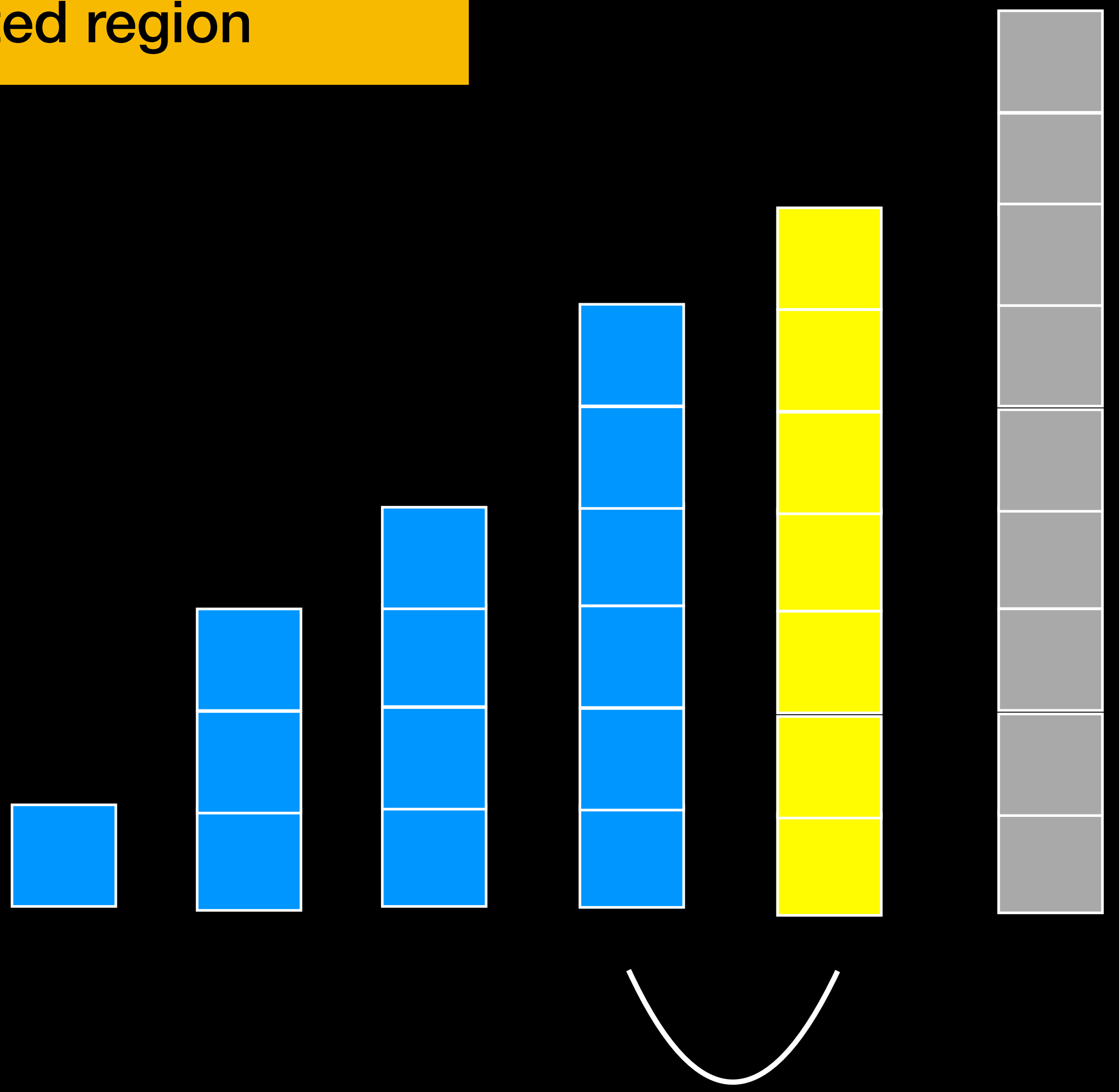


Insertion Sort

Unsorted

Sorted

Pick first element in unsorted region and put it in right place in sorted region

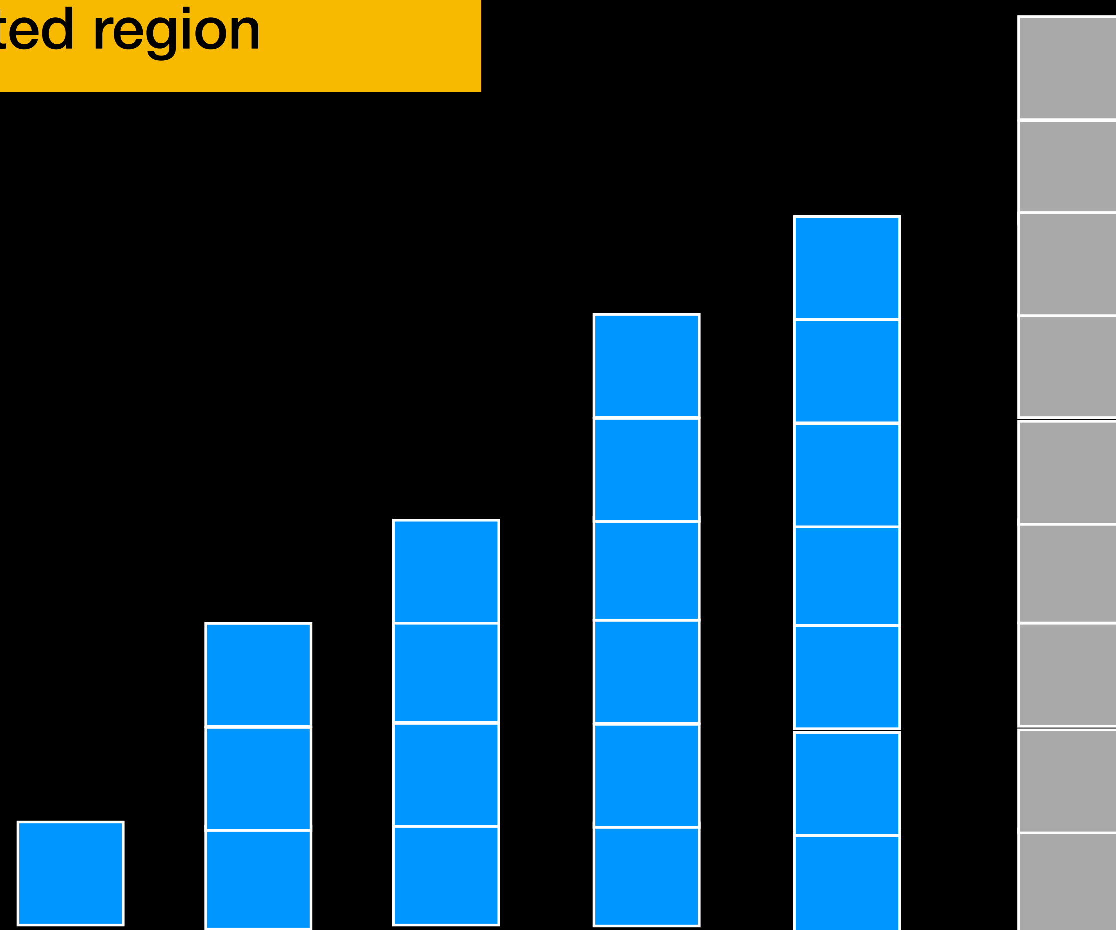


Insertion Sort

Unsorted

Sorted

Pick first element in unsorted region and put it in right place in sorted region

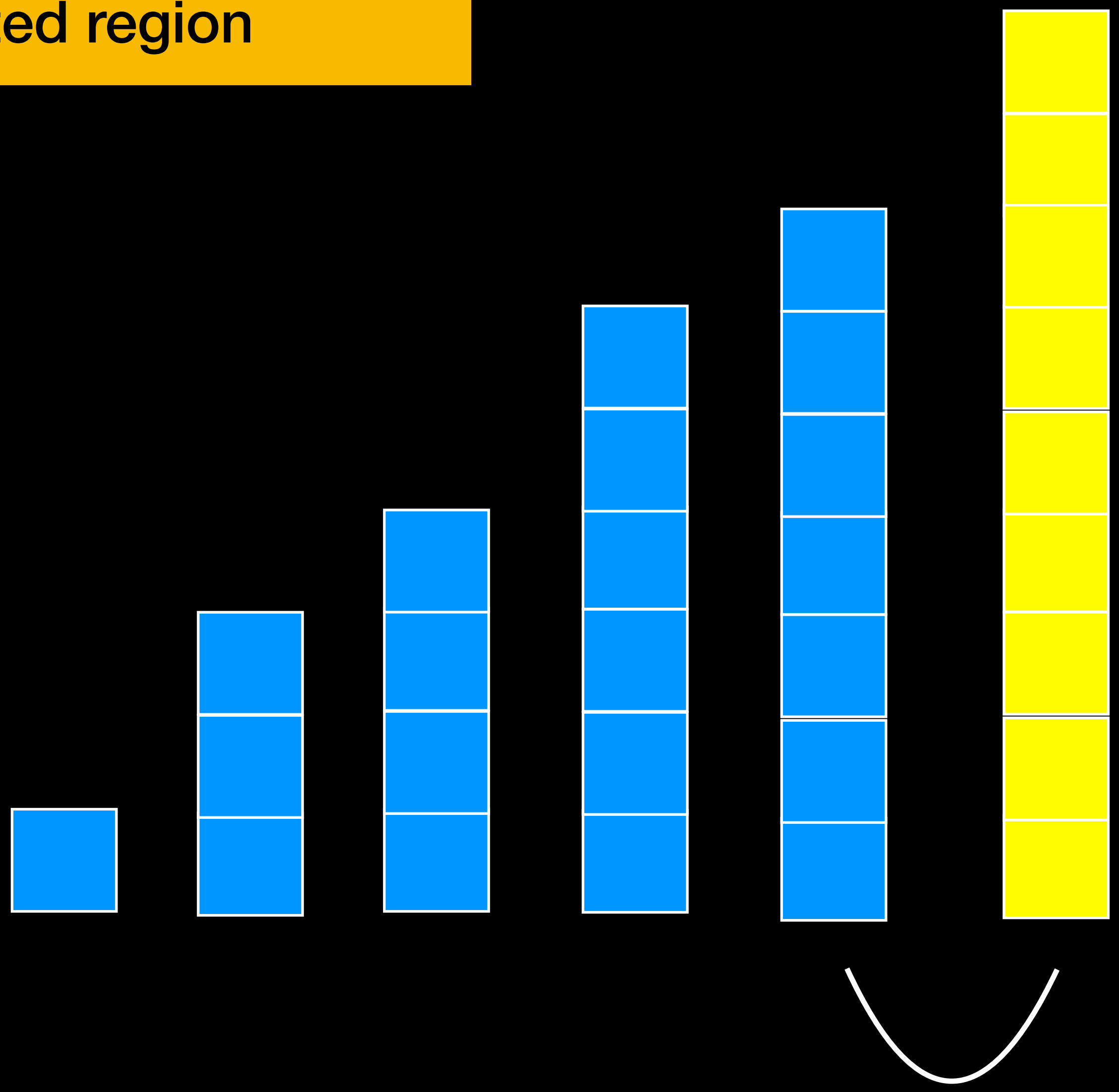


Insertion Sort

Unsorted

Sorted

Pick first element in unsorted region and put it in right place in sorted region

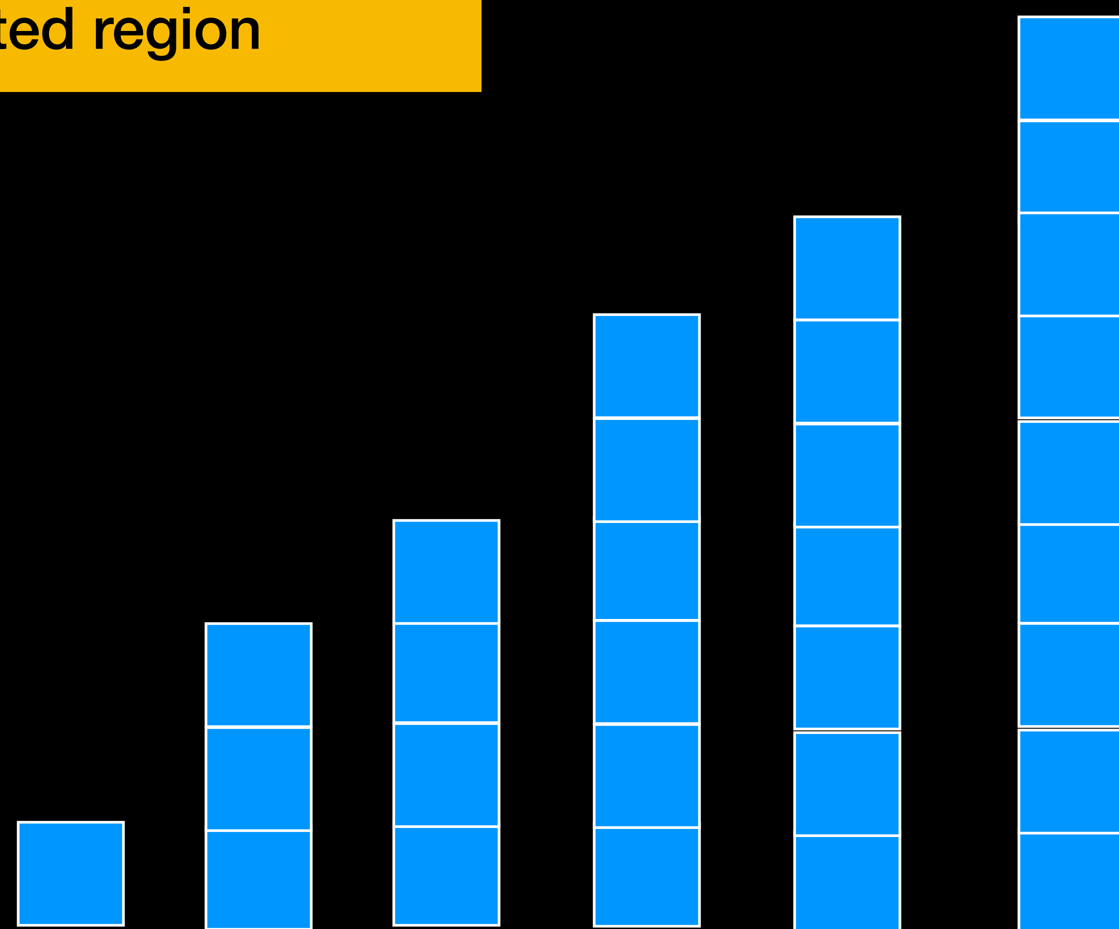


Insertion Sort

Unsorted

Sorted

Pick first element in unsorted region and put it in right place in sorted region



Insertion Sort Analysis

Execution time DOES depend on initial arrangement of data

Worst case: $O(n^2)$ comparisons and data moves

Best case: $O(n)$ comparisons and data moves

Stable

If array is already sorted Insertion sort will do only n comparisons and no swaps => good choice for small n and data likely somewhat sorted

```cpp
template <class Comparable>
void insertionSort(const std::vector<Comparable>& the_array)
{
   int size = the_array.size();
   // unsorted = first index of the unsorted region,
   // Initially, sorted region is the_array[0],
   // unsorted region is the_array[1 ... size-1].
   // In general, sorted region is the_array[0 ... unsorted-1],
   // unsorted region the_array[unsorted ... size-1]
   for (int unsorted = 1; unsorted < size; unsorted++)
   {
      // At this point, the_array[0 ... unsorted-1] is sorted.
      // Keep swapping item to be inserted currently at the_array[unsorted]
      // with items at lower indices as long as its value is >
      int current = unsorted; //the index of the item currently being inserted
      while ((current > 0) && (the_array[current - 1] > the_array[current]))
      {
         std::swap(the_array[current], the_array[current - 1]);  // swap
         current--;
      }  // end while
   }  // end for
}  // end insertionSort
```

Pass O(n)

O(n)

```
template <class Comparable>
void insertionSort(const std::vector<Comparable>& the_array)
{
   int size = the_array.size();
   // unsorted = first index of the unsorted region,
   // Initially, sorted region is the_array[0],
   // unsorted region is the_array[1 ... size-1].
   // In general, sorted region is the_array[0 ... unsorted-1],
   // unsorted region the_array[unsorted ... size-1]
   for (int unsorted = 1; unsorted < size; unsorted++)
   {
      // At this point, the_array[0 ... unsorted-1] is sorted.
      // Keep swapping item to be inserted currently at the_array[unsorted]
      // with items at lower indices as long as its value is >
      int current = unsorted; //the index of the item currently being inserted
      while ((current > 0) && (the_array[current - 1] > the_array[current]))
      {
         std::swap(the_array[current], the_array[current - 1]);  // swap
         current--;
      }  // end while
   }  // end for
}  // end insertionSort
```

$O(n^2)$

Raise your hand if you had Insertion Sort

What we have so far

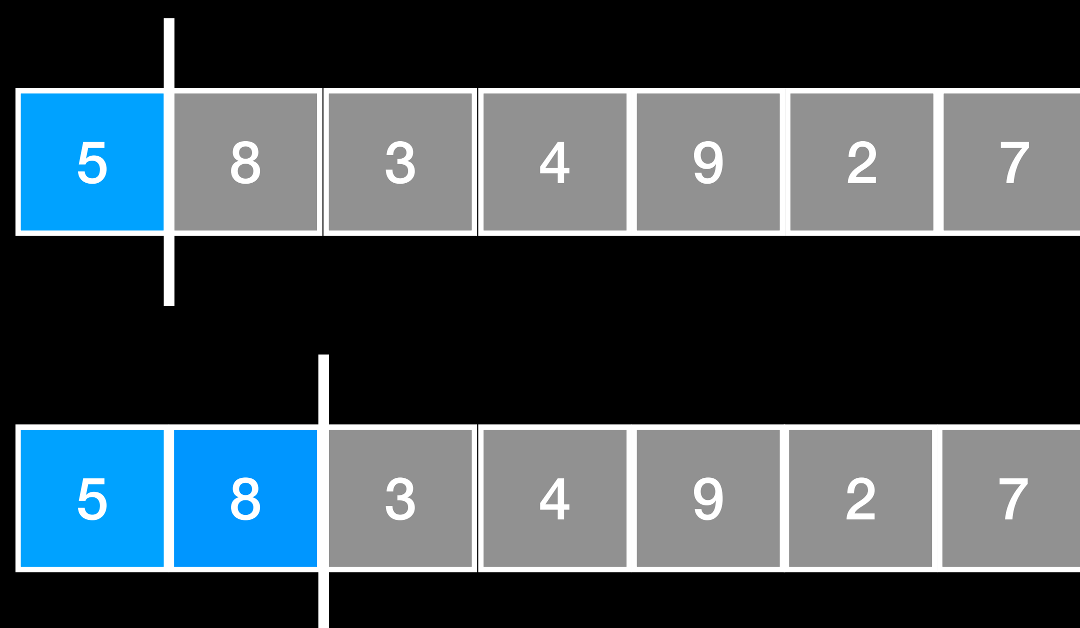
	Worst Case	Best Case
Selection Sort	$O(n^2)$	$O(n^2)$
Bubble Sort	$O(n^2)$	$O(n)$
Insertion Sort	$O(n^2)$	$O(n)$

Pick first element in unsorted region and put it in right place in sorted region

Lecture Activity

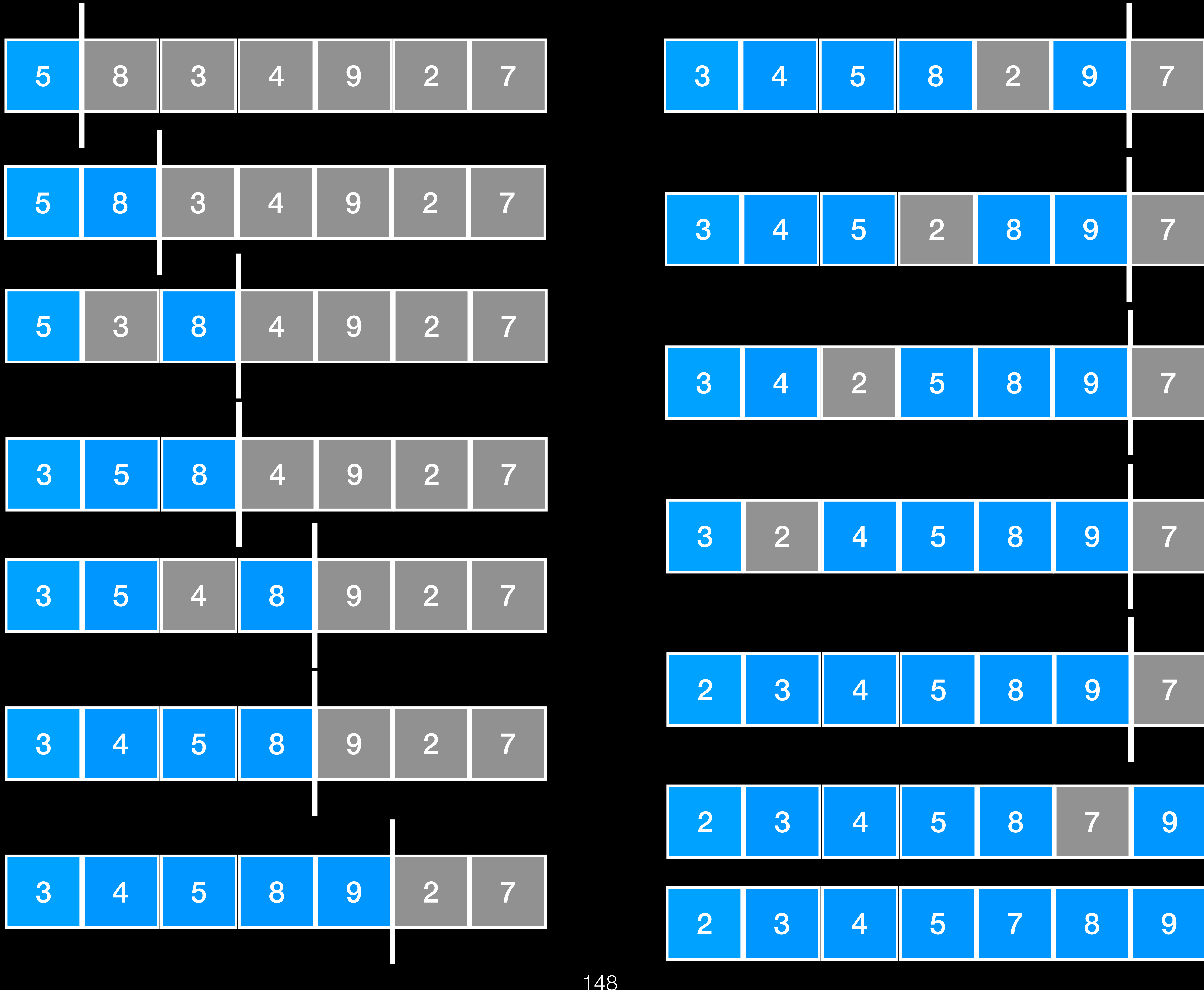
Sort the array using **Insertion Sort**

Show the entire array after each comparison/swap operation and at each step mark clearly the division between the sorted and unsorted portions of the array



Lecture Assignment on Gradescope

Login and submit NOW!!!


5 8 3 4 9 2 7
5 8 3 4 9 2 7
5 3 8 4 9 2 7
3 5 8 4 9 2 7
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3 4 5 8 2 9 7
3 4 5 2 8 9 7
3 4 2 5 8 9 7
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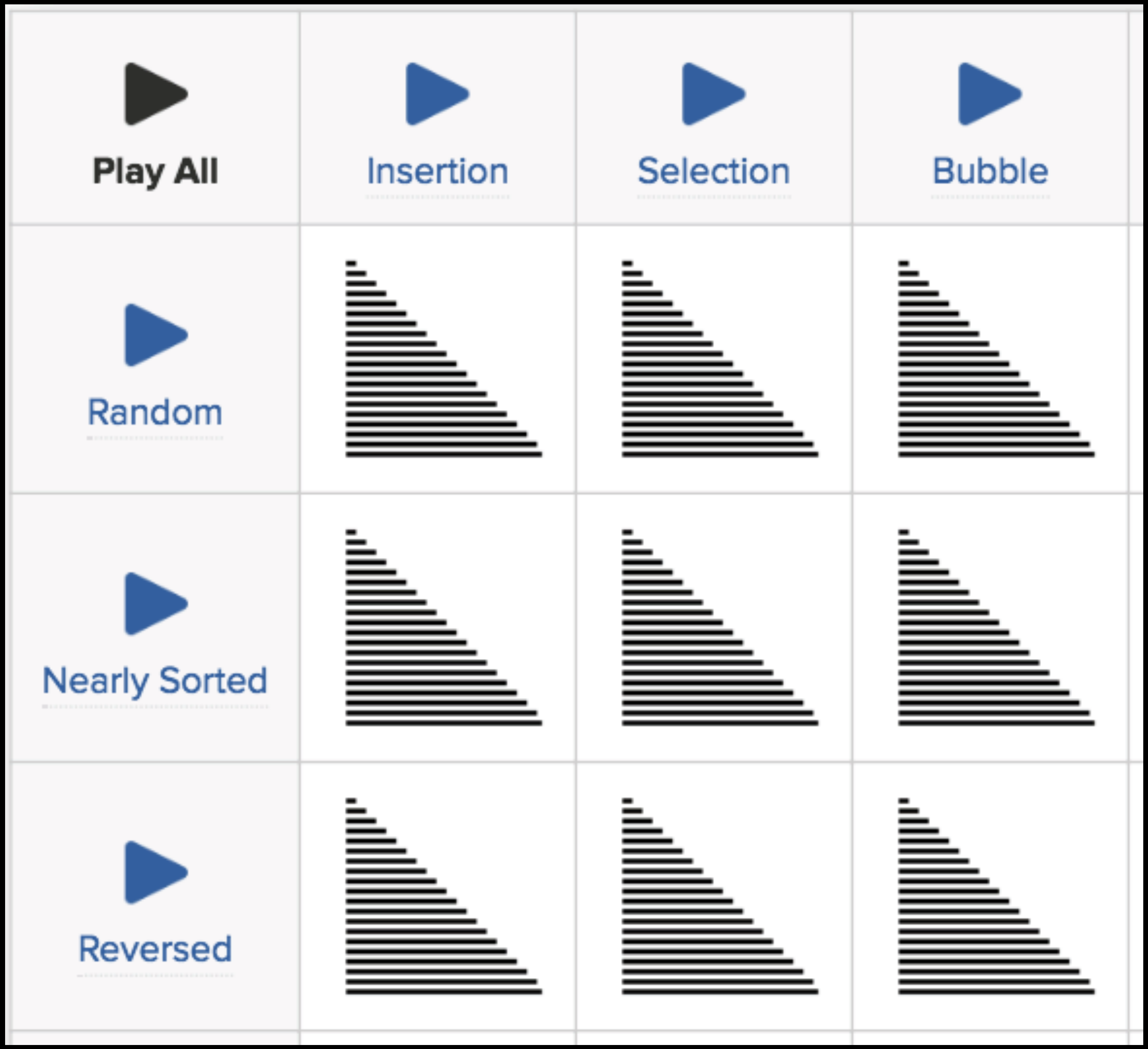
2 3 4 5 8 7 9
2 3 4 5 7 8 9

https://www.toptal.com/developers/sorting-algorithms



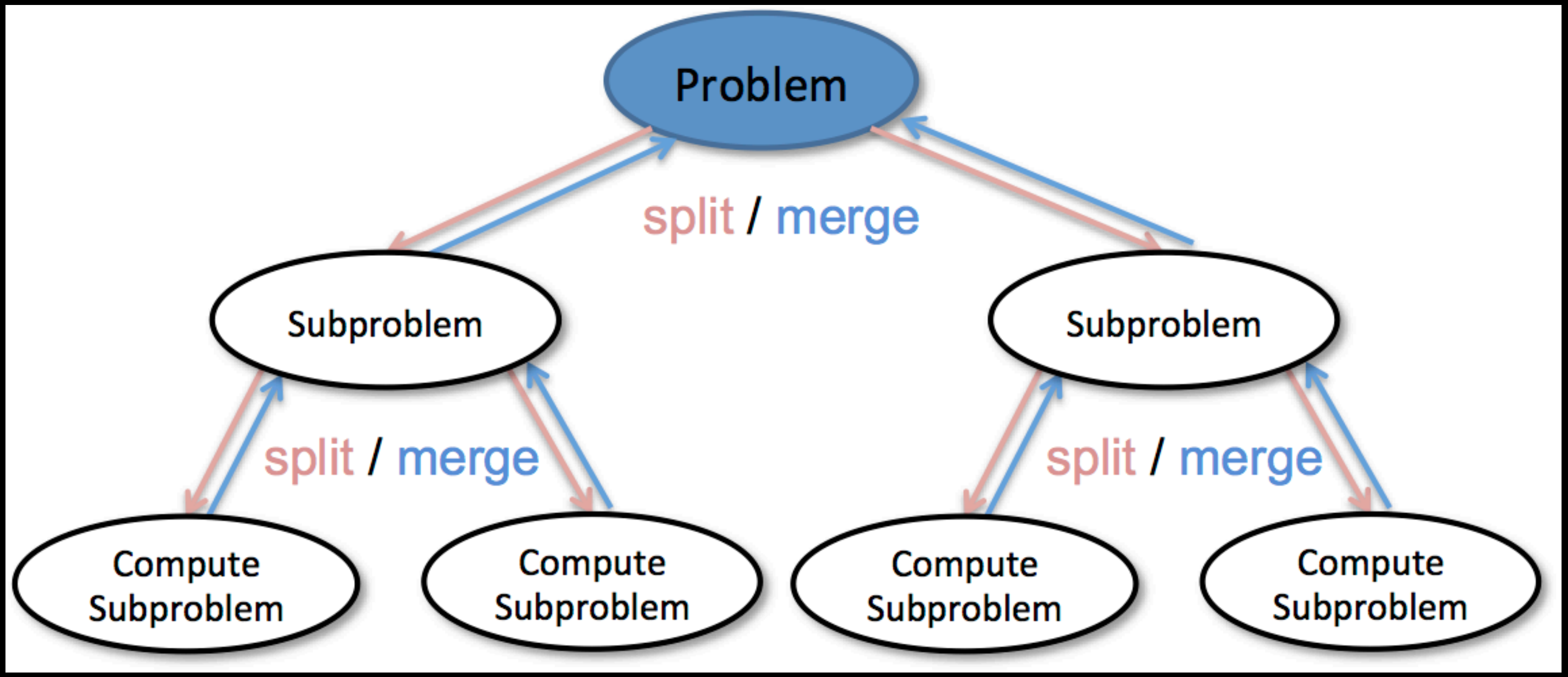
What we have so far

	Worst Case	Best Case
Selection Sort	$O(n^2)$	$O(n^2)$
Bubble Sort	$O(n^2)$	$O(n)$
Insertion Sort	$O(n^2)$	$O(n)$

Can we do better?

Can we do better?

Divide and Conquer!!!



Merge Sort

Understanding $O(n^2)$

100	14	3	43	200	274	523	108	76	195	599	158	2	260	11	64	932	5

$T(n)$

Understanding $O(n^2)$

100	14	3	43	200	274	523	108	76	195	599	158	2	260	11	64	932	5

T(n)

100	14	3	43	200	274	523	108	76

195	599	158	2	260	11	64	932	5

Understanding $O(n^2)$

100	14	3	43	200	274	523	108	76	195	599	158	2	260	11	64	932	5

$T(n)$

100	14	3	43	200	274	523	108	76

$T(^1/_2 n)$

195	599	158	2	260	11	64	932	5

$T(^1/_2 n)$

Understanding $O(n^2)$

100	14	3	43	200	274	523	108	76	195	599	158	2	260	11	64	932	5

$T(n)$

100	14	3	43	200	274	523	108	76

195	599	158	2	260	11	64	932	5

$T(^1/_2 n)$ $T(^1/_2 n)$

$(n/2)^2 = n^2/4$

Understanding $O(n^2)$

100	14	3	43	200	274	523	108	76	195	599	158	2	260	11	64	932	5

$T(n)$

100	14	3	43	200	274	523	108	76

$T(\frac{1}{2}n) \approx \frac{1}{4} T(n)$

195	599	158	2	260	11	64	932	5

$T(\frac{1}{2}n) \approx \frac{1}{4} T(n)$

$$(n/2)^2 = n^2/4$$

Understanding $O(n^2)$

100	14	3	43	200	274	523	108	76	195	599	158	2	260	11	64	932	5

$T(n)$

3	14	43	76	100	108	200	274	523

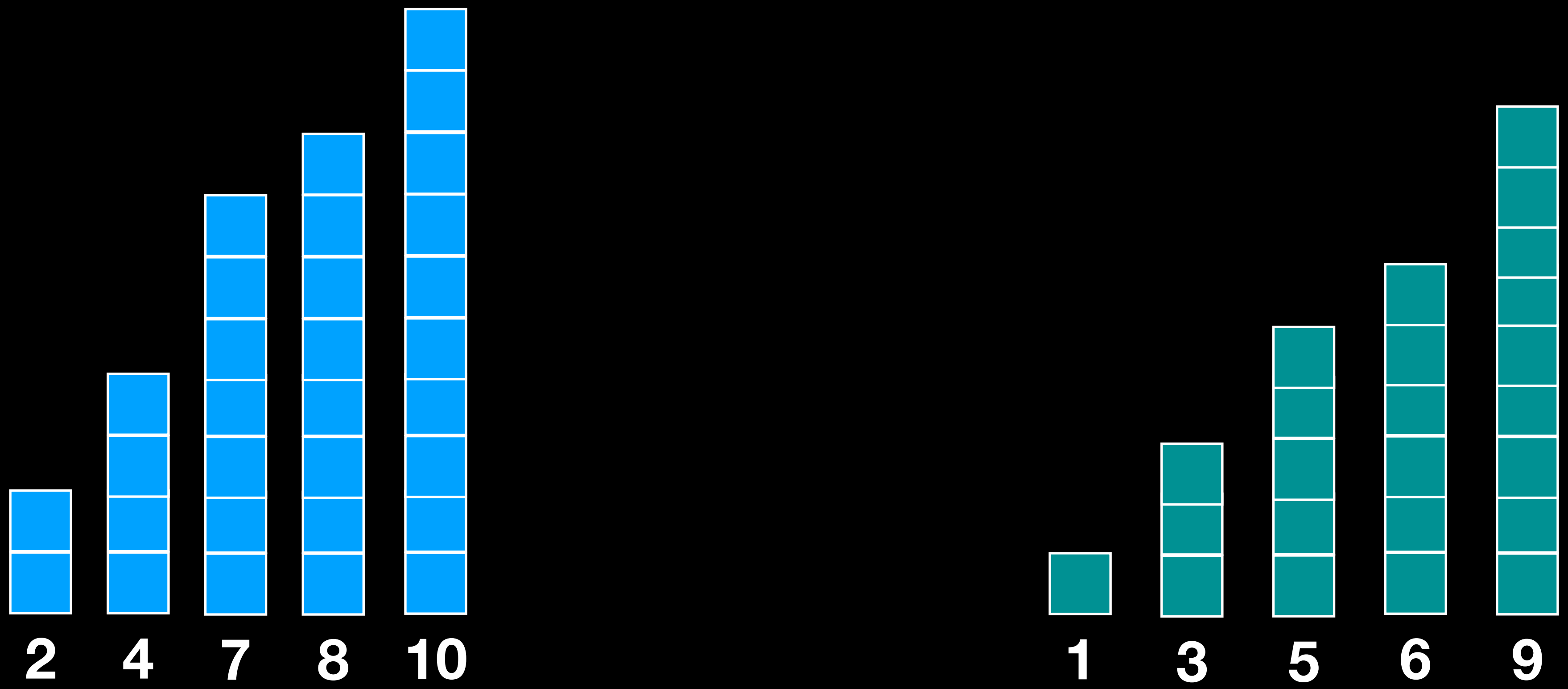
2	5	11	64	158	195	260	599	932

$T(\frac{1}{2}n) \approx \frac{1}{4} T(n)$

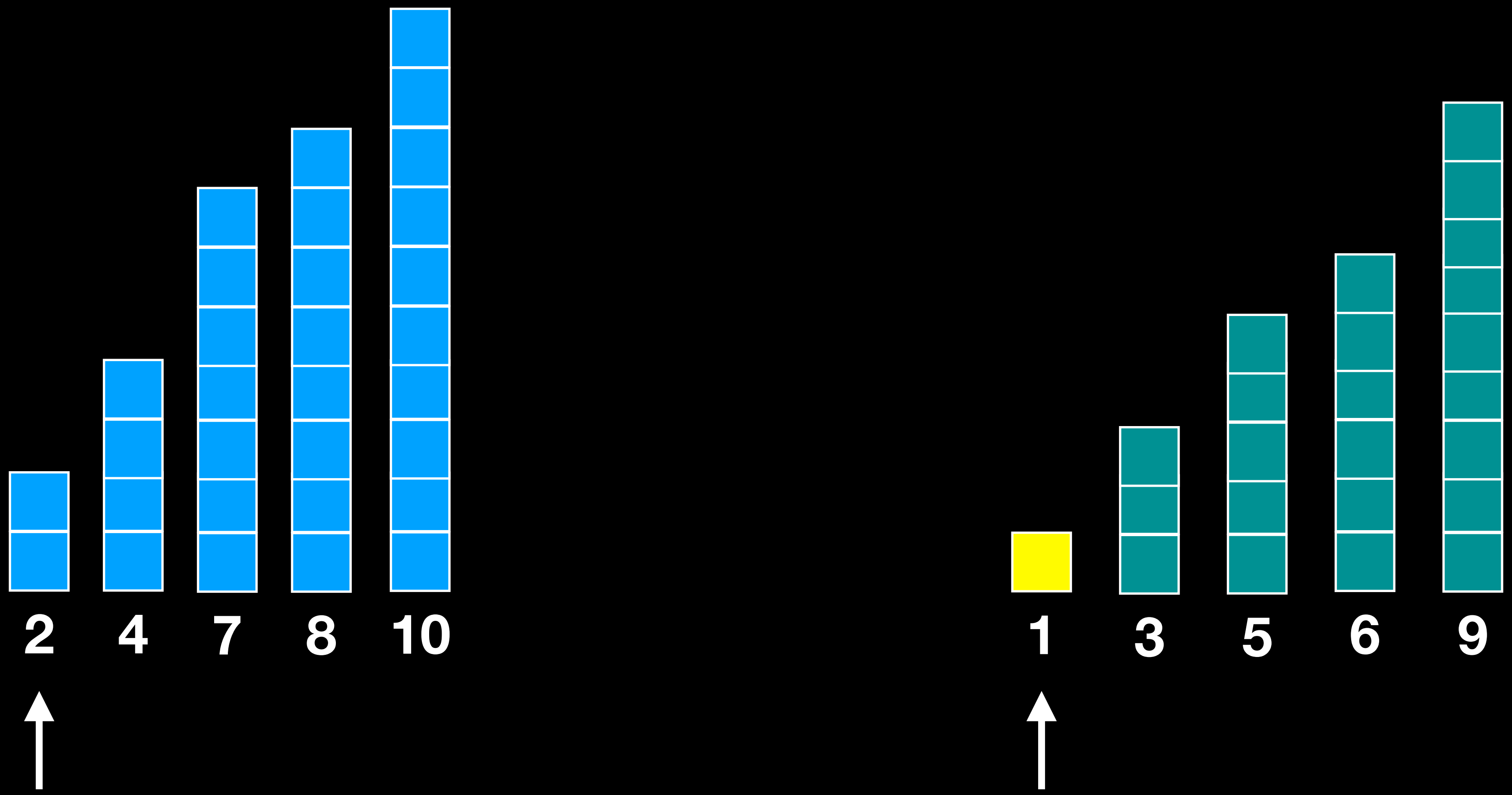
$T(\frac{1}{2}n) \approx \frac{1}{4} T(n)$

$(n/2)^2 = n^2/4$

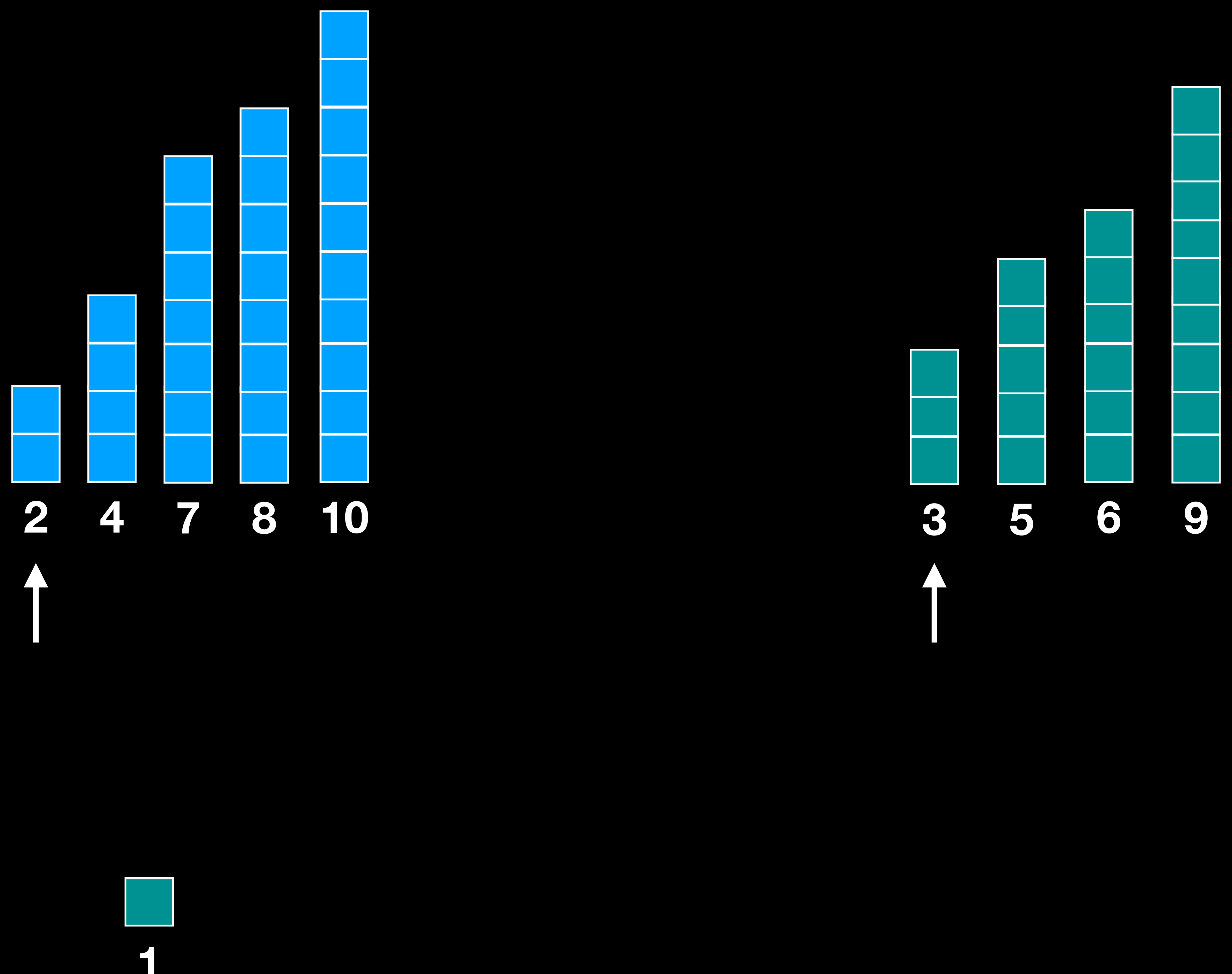
Key Insight: Merge is linear



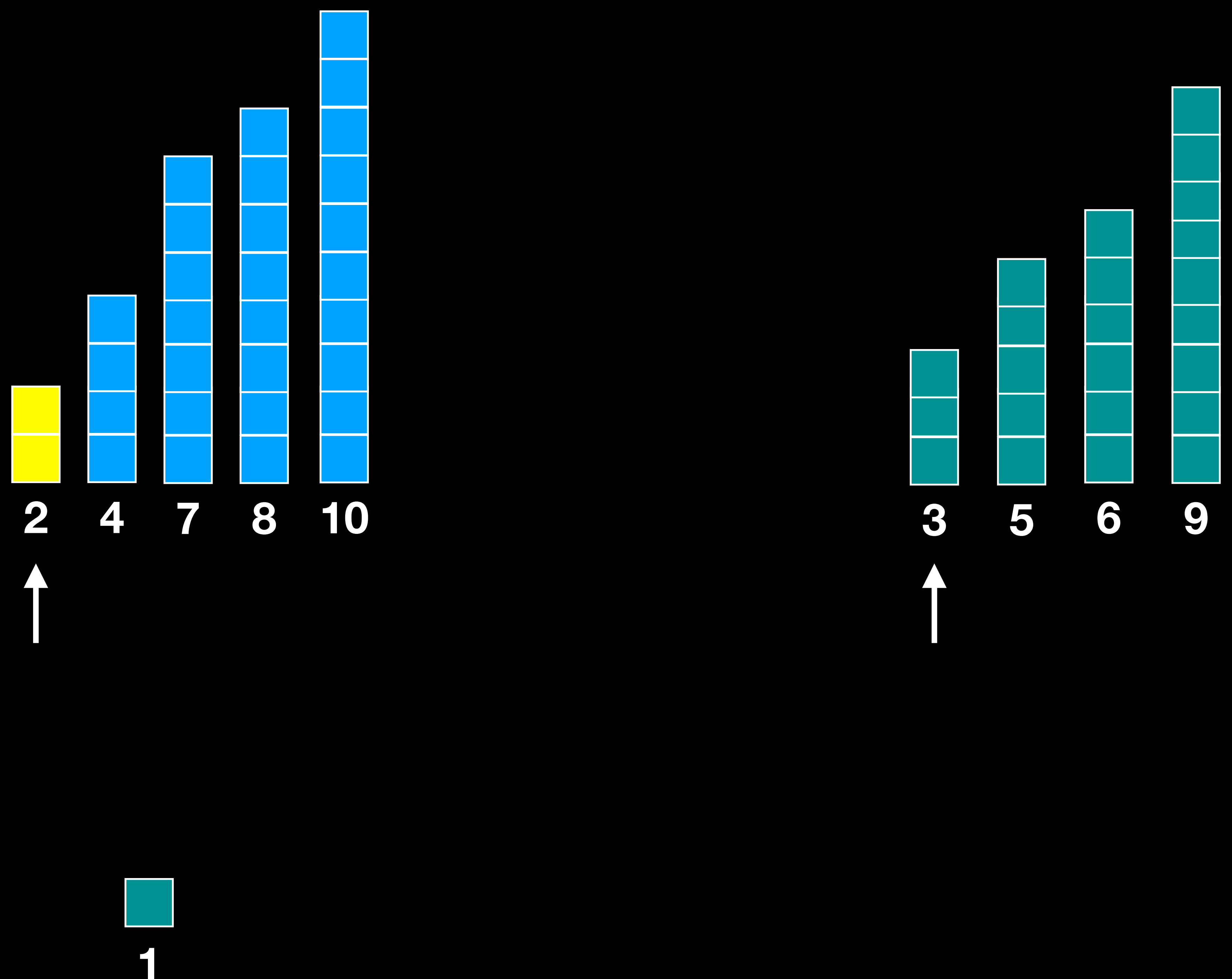
Key Insight: Merge is linear



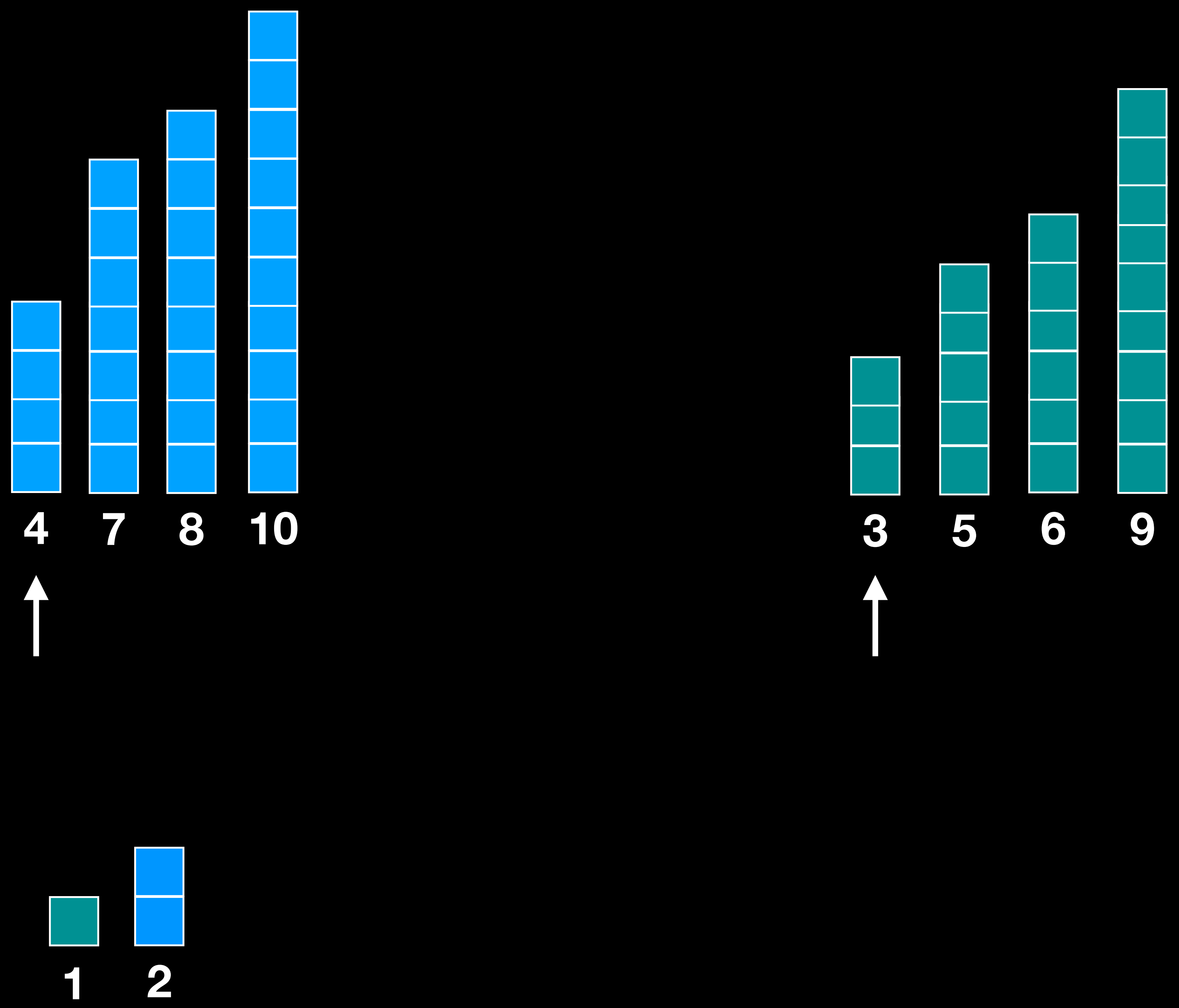
Key Insight: Merge is linear



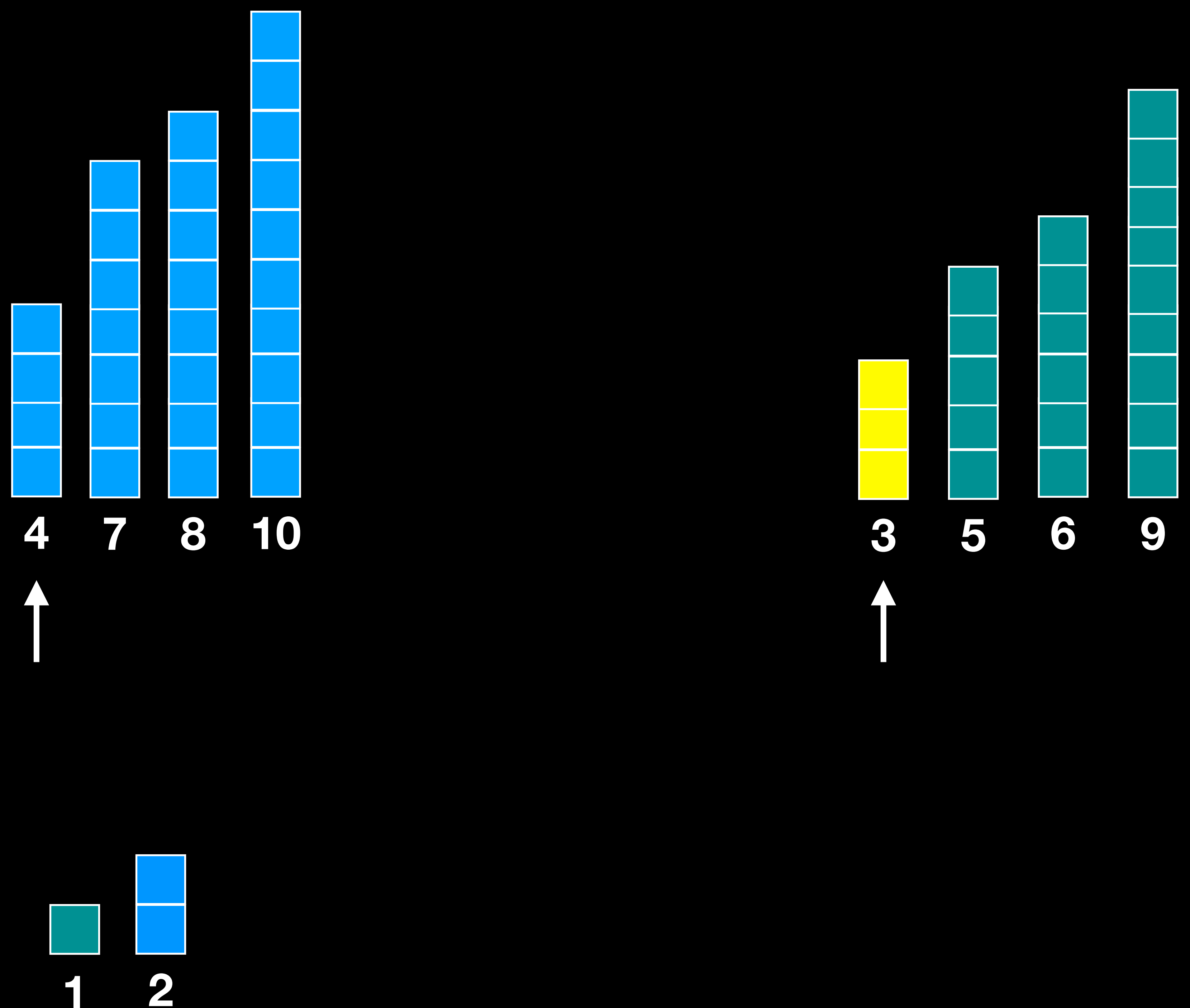
Key Insight: Merge is linear



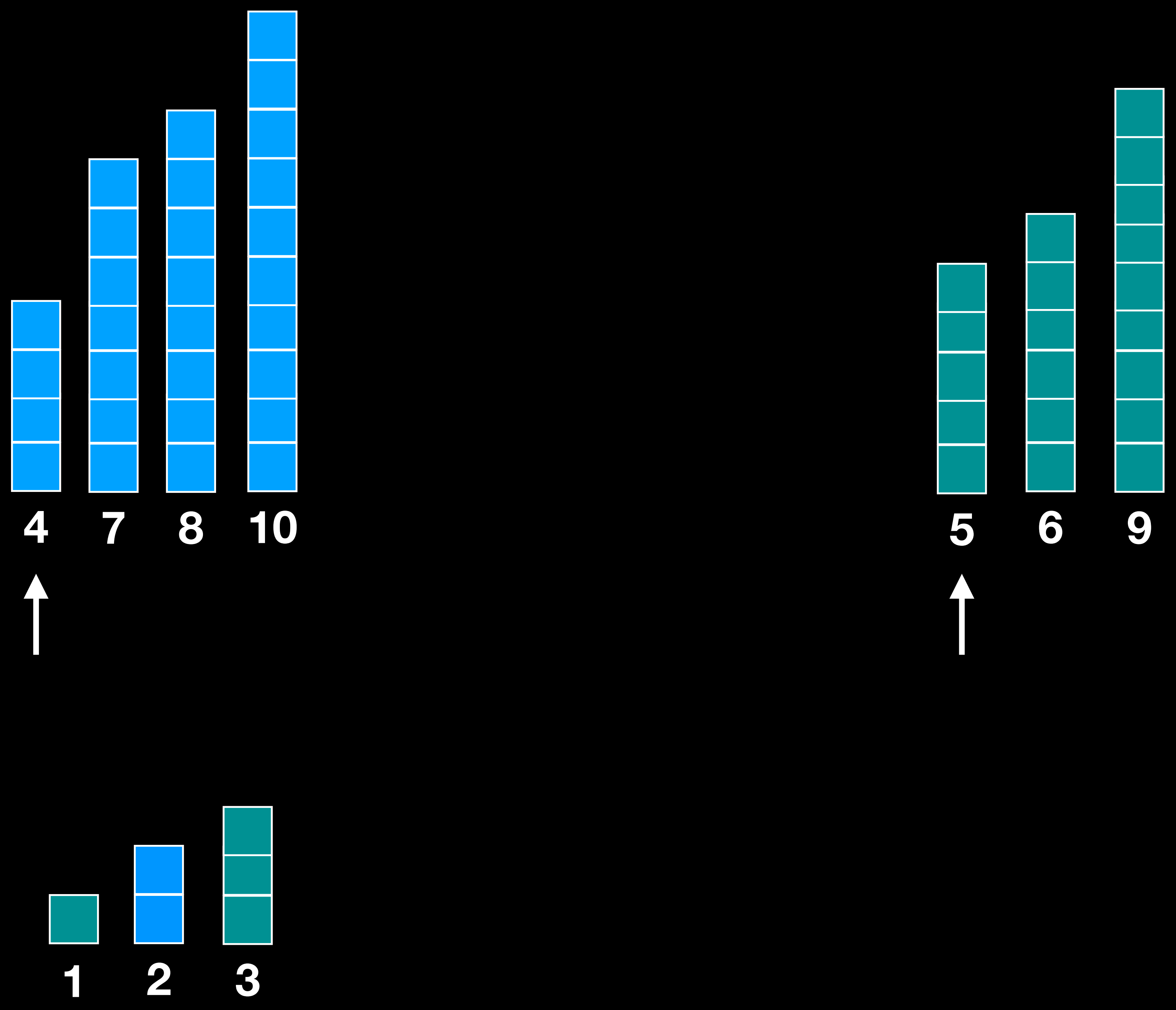
Key Insight: Merge is linear



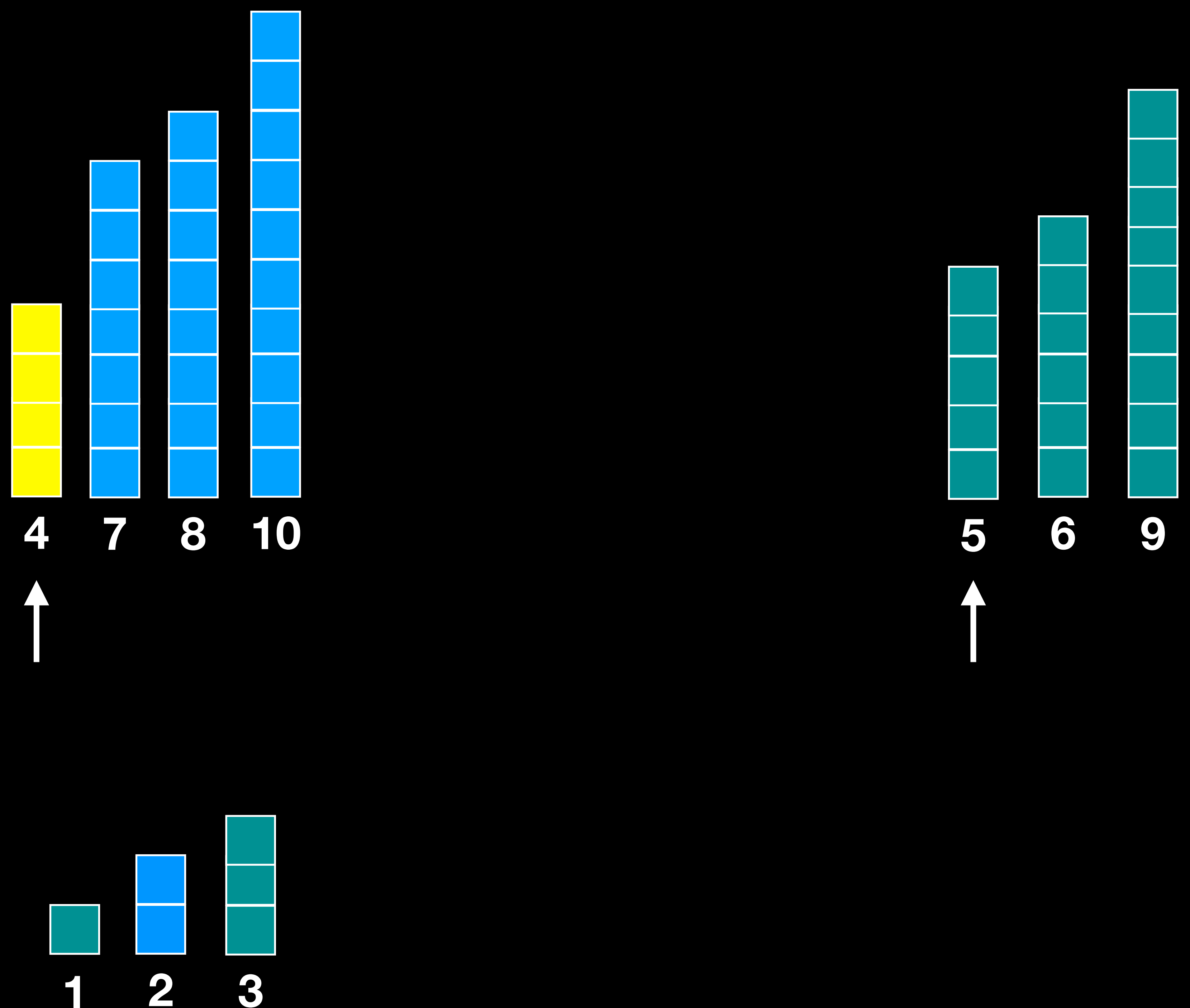
Key Insight: Merge is linear



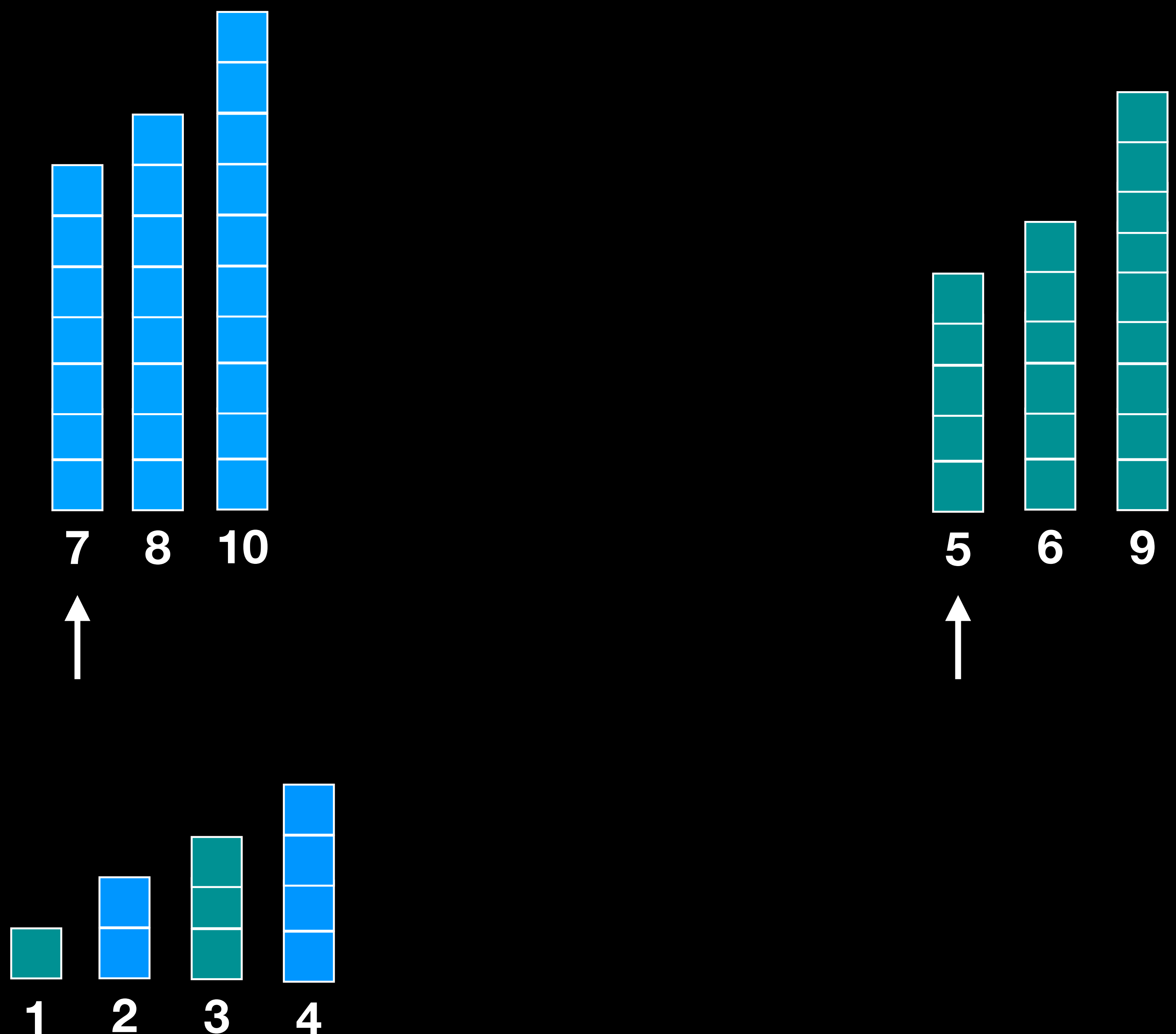
Key Insight: Merge is linear



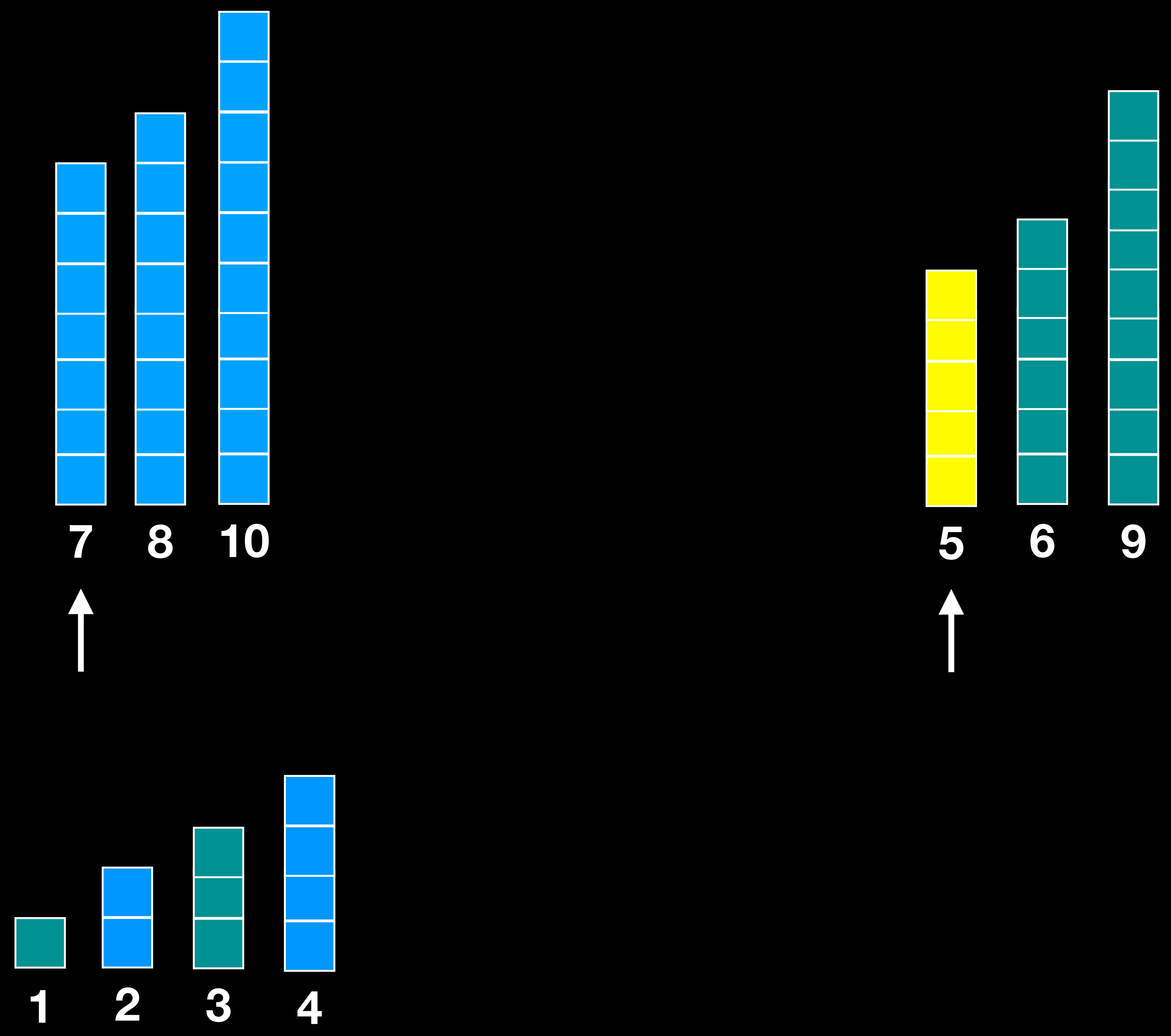
Key Insight: Merge is linear



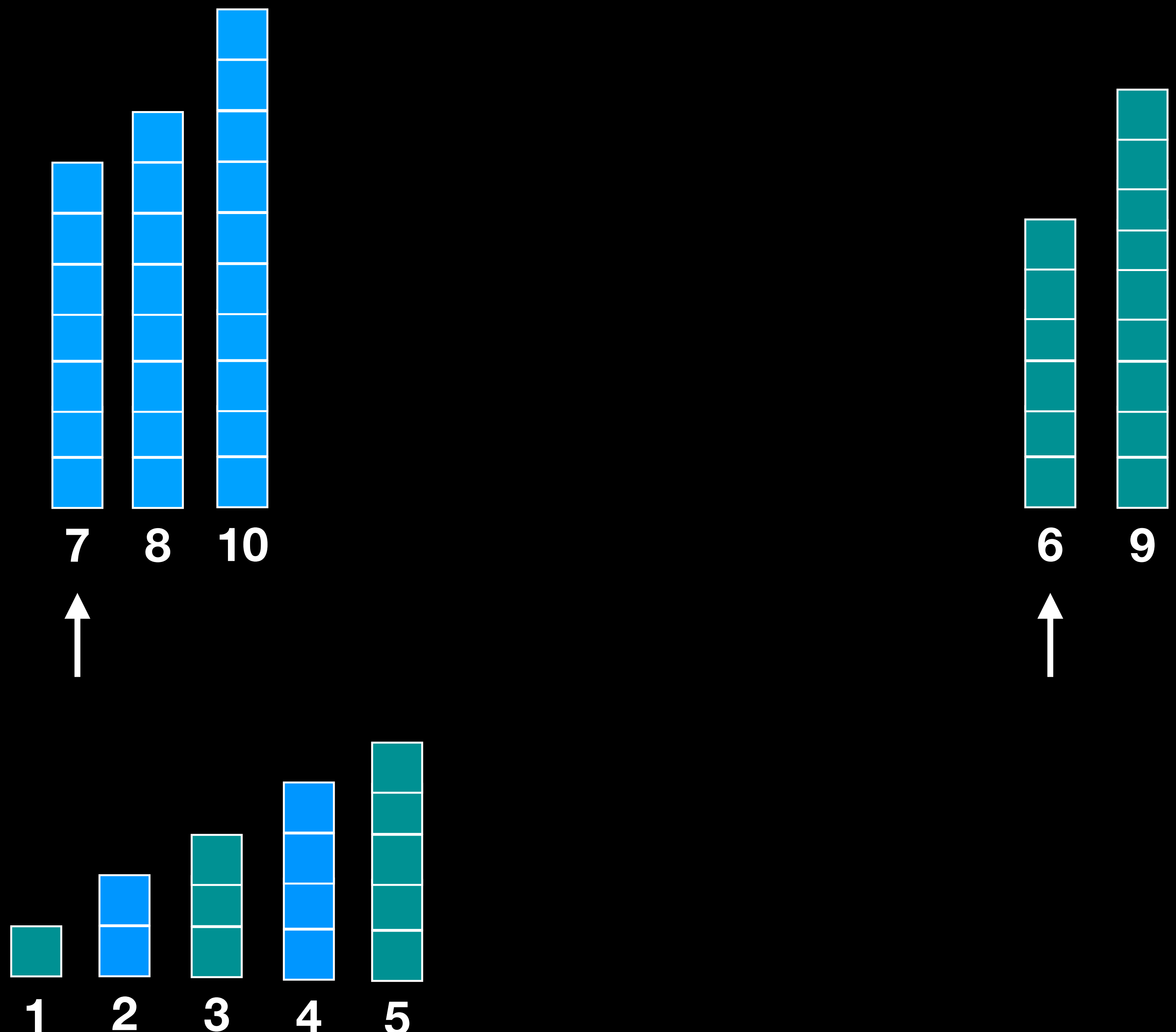
Key Insight: Merge is linear



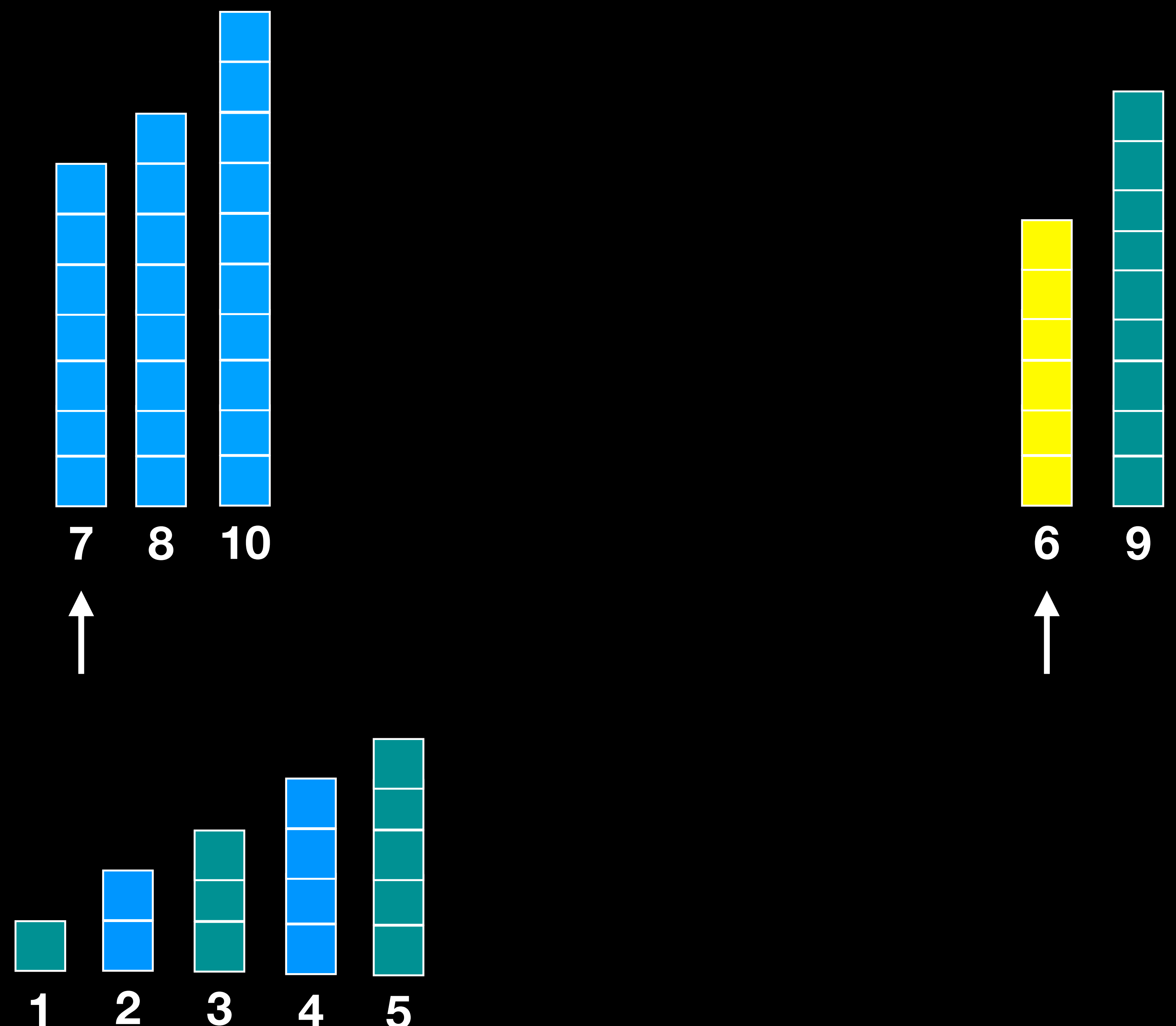
Key Insight: Merge is linear



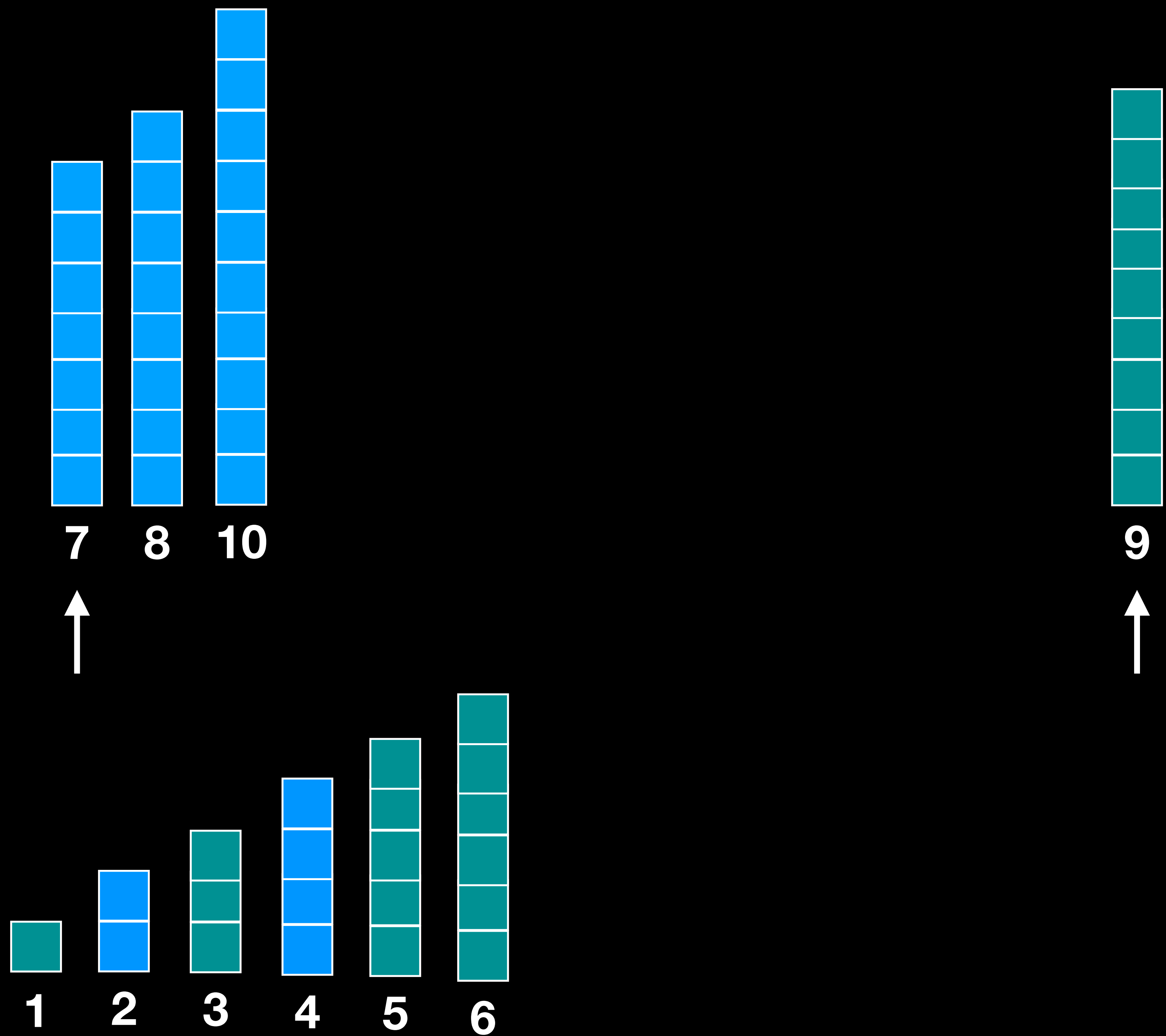
Key Insight: Merge is linear



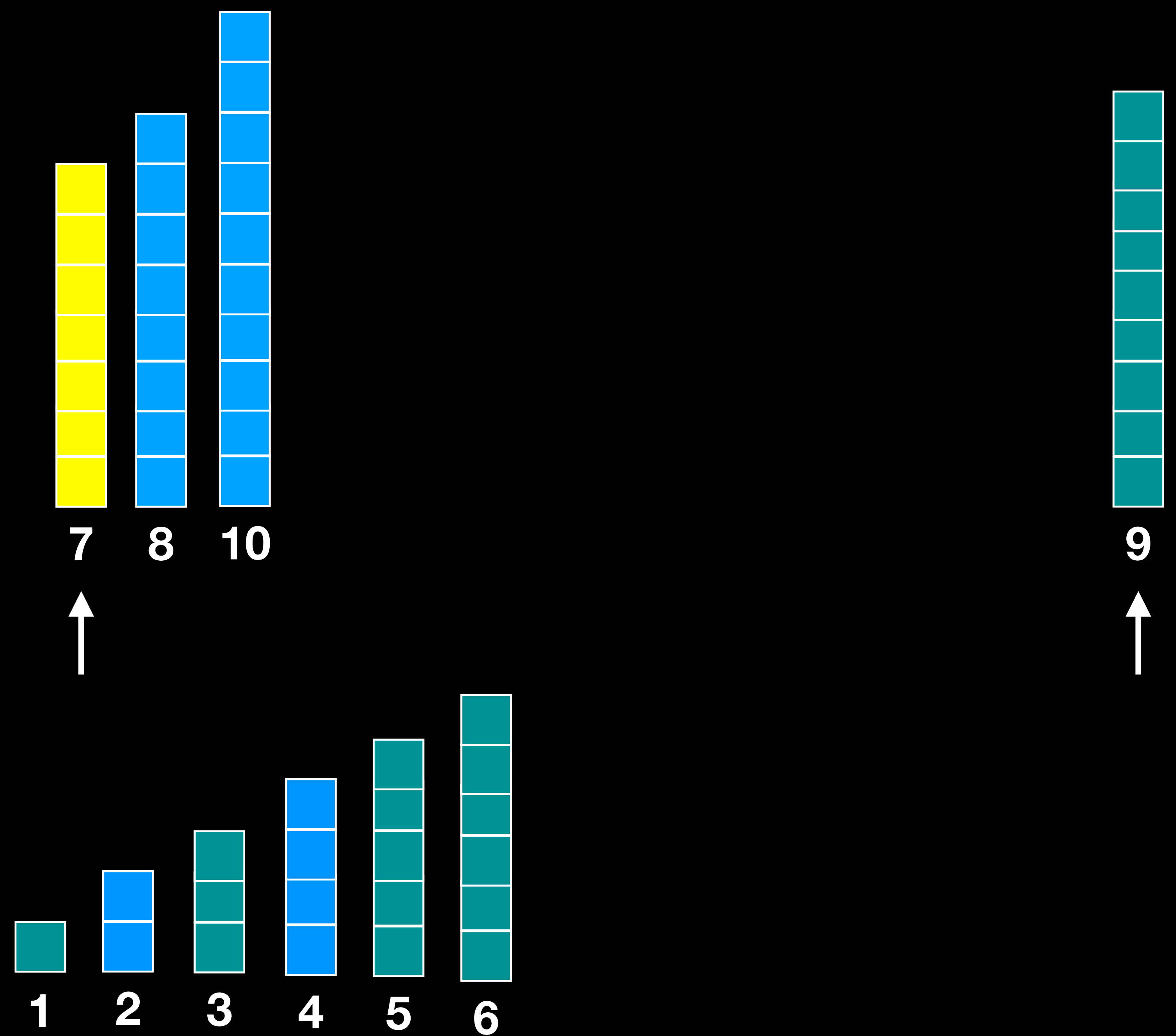
Key Insight: Merge is linear



Key Insight: Merge is linear



Key Insight: Merge is linear



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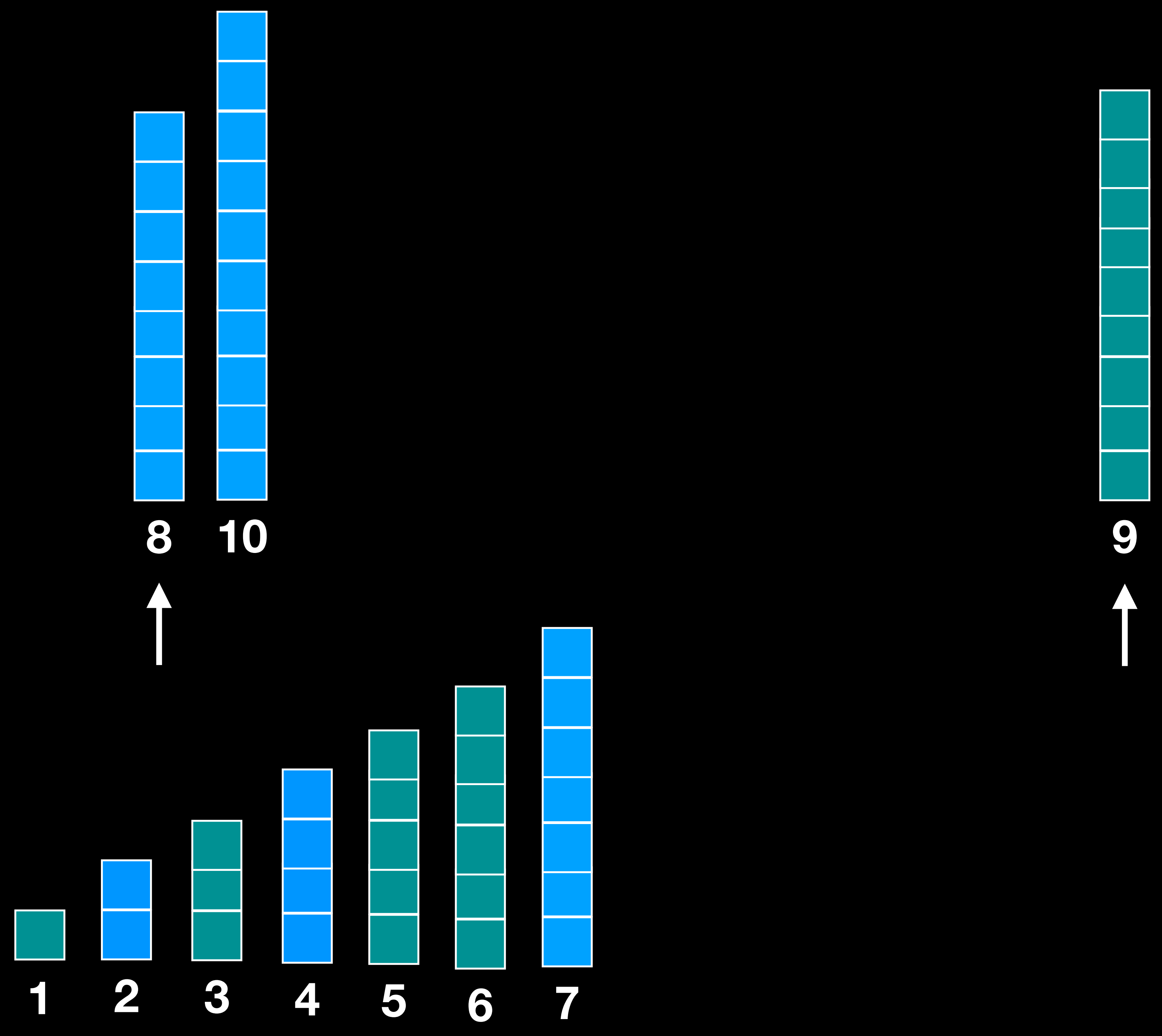
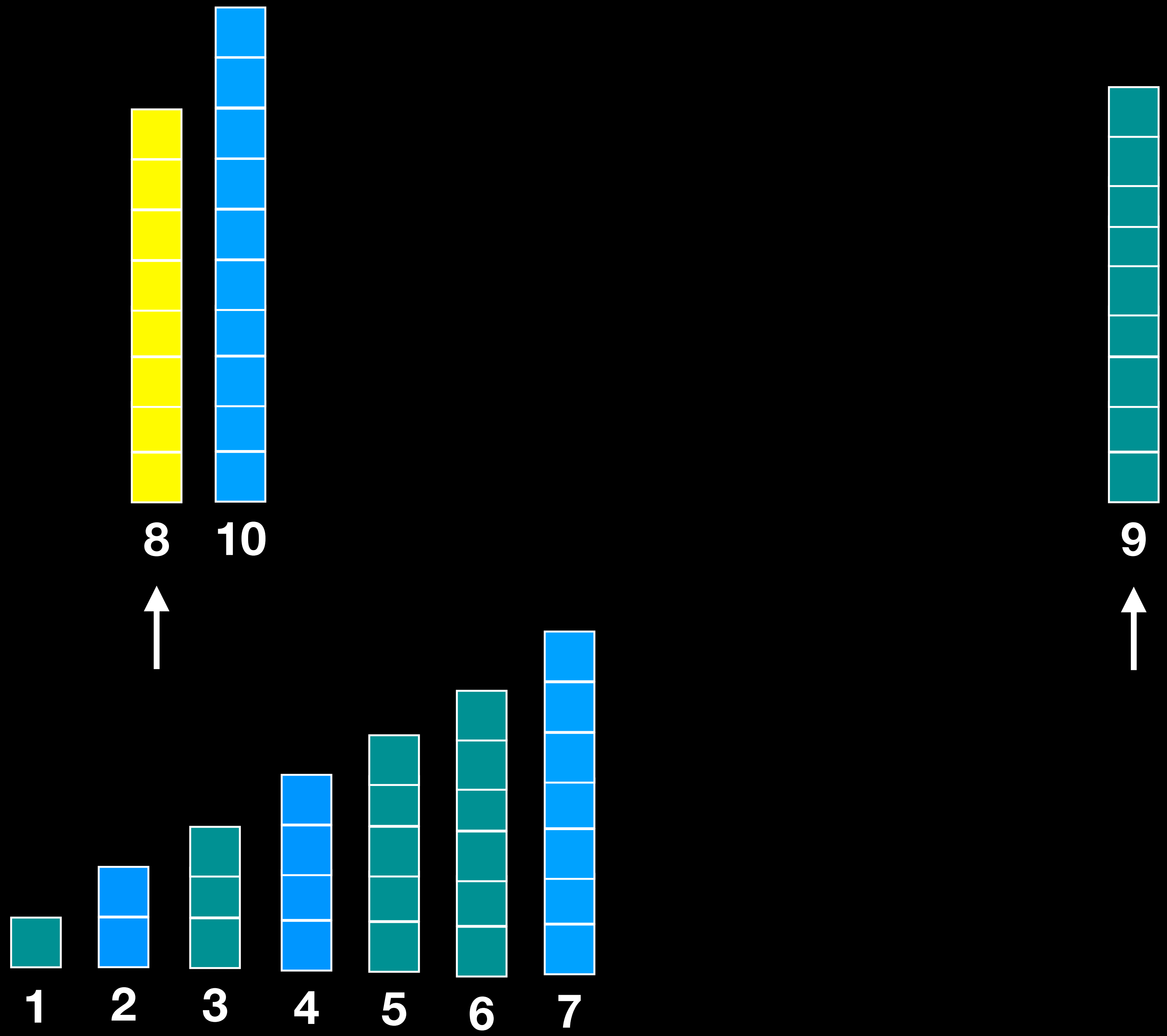
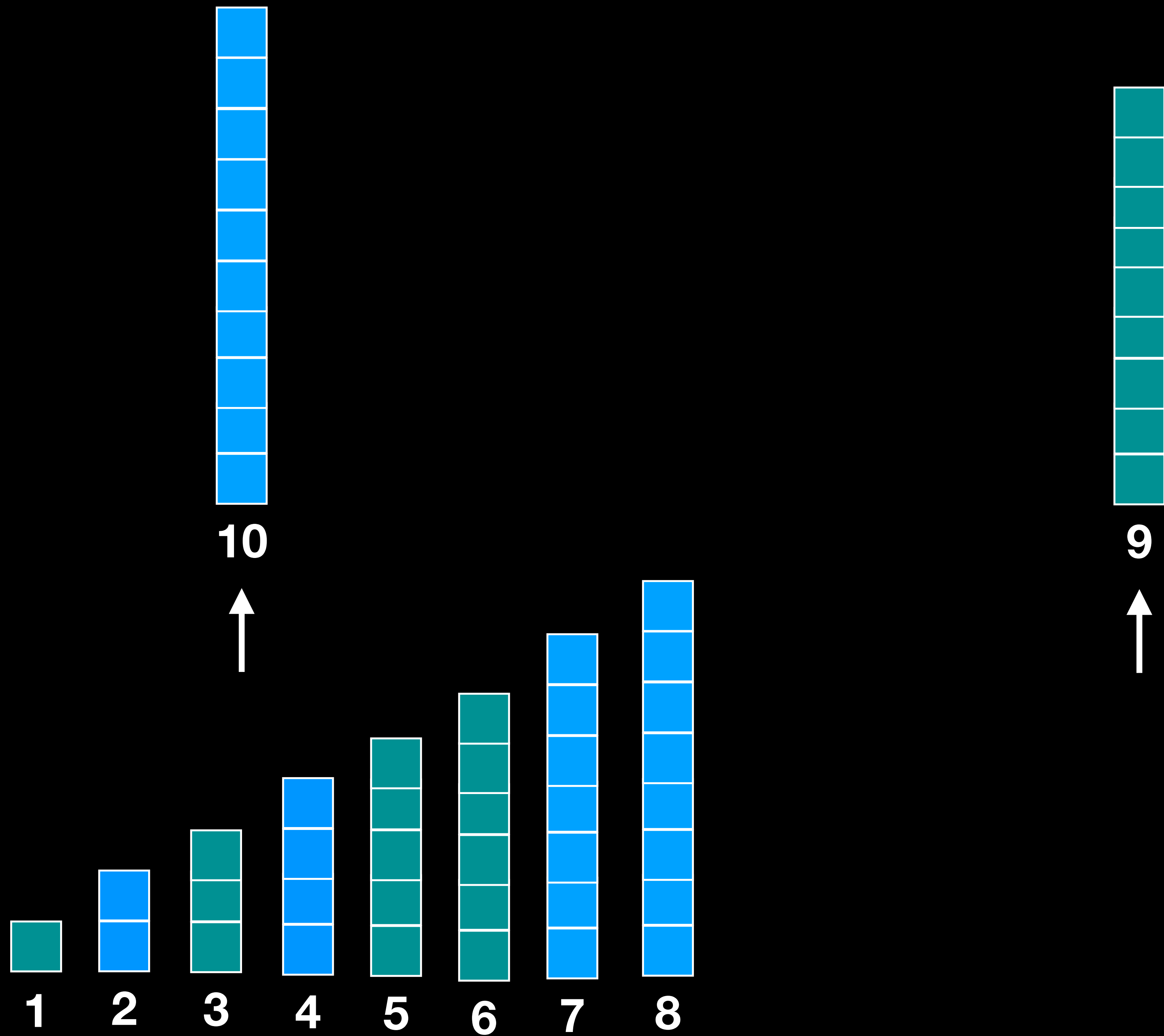


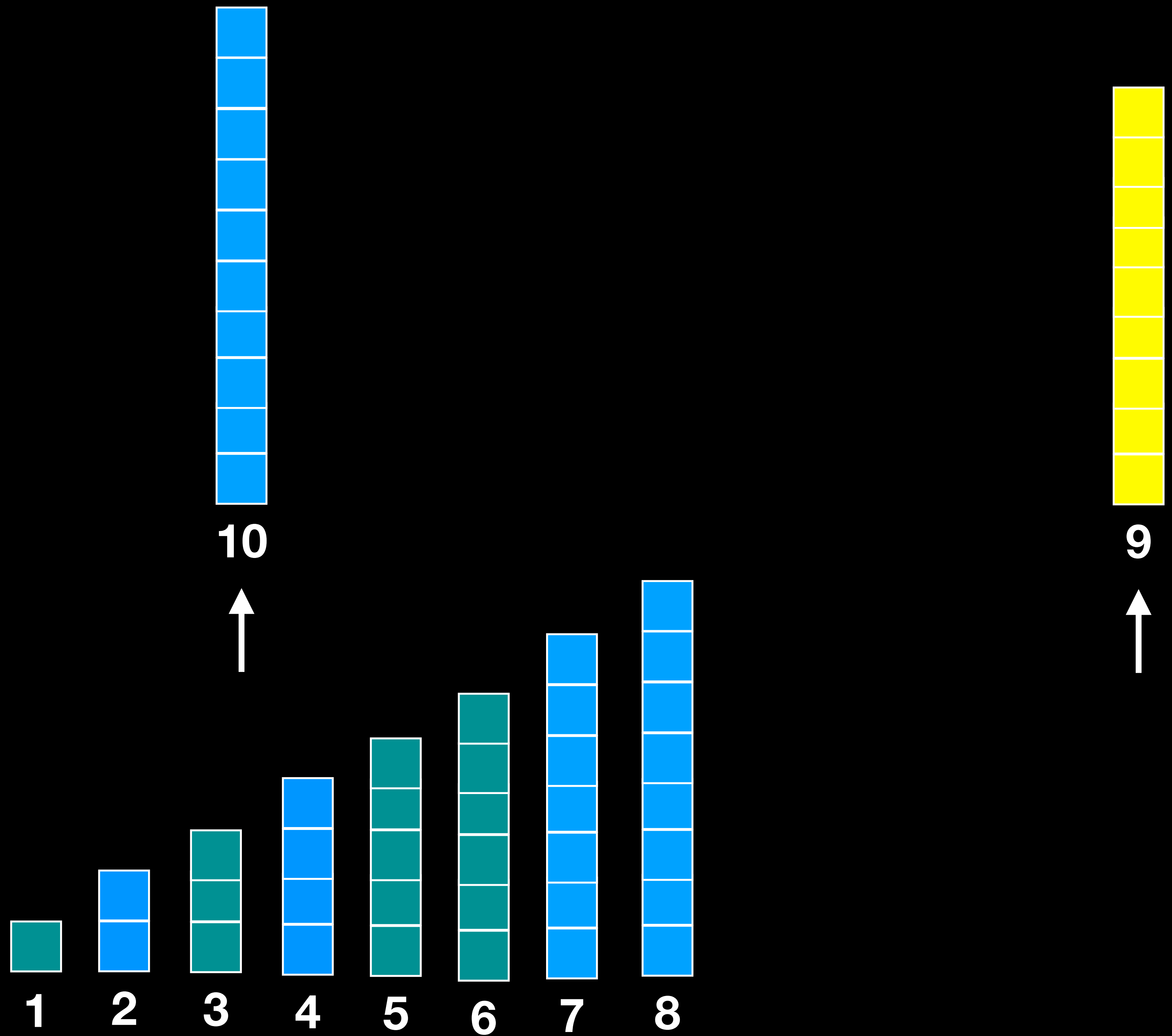
Key Insight: Merge is linear



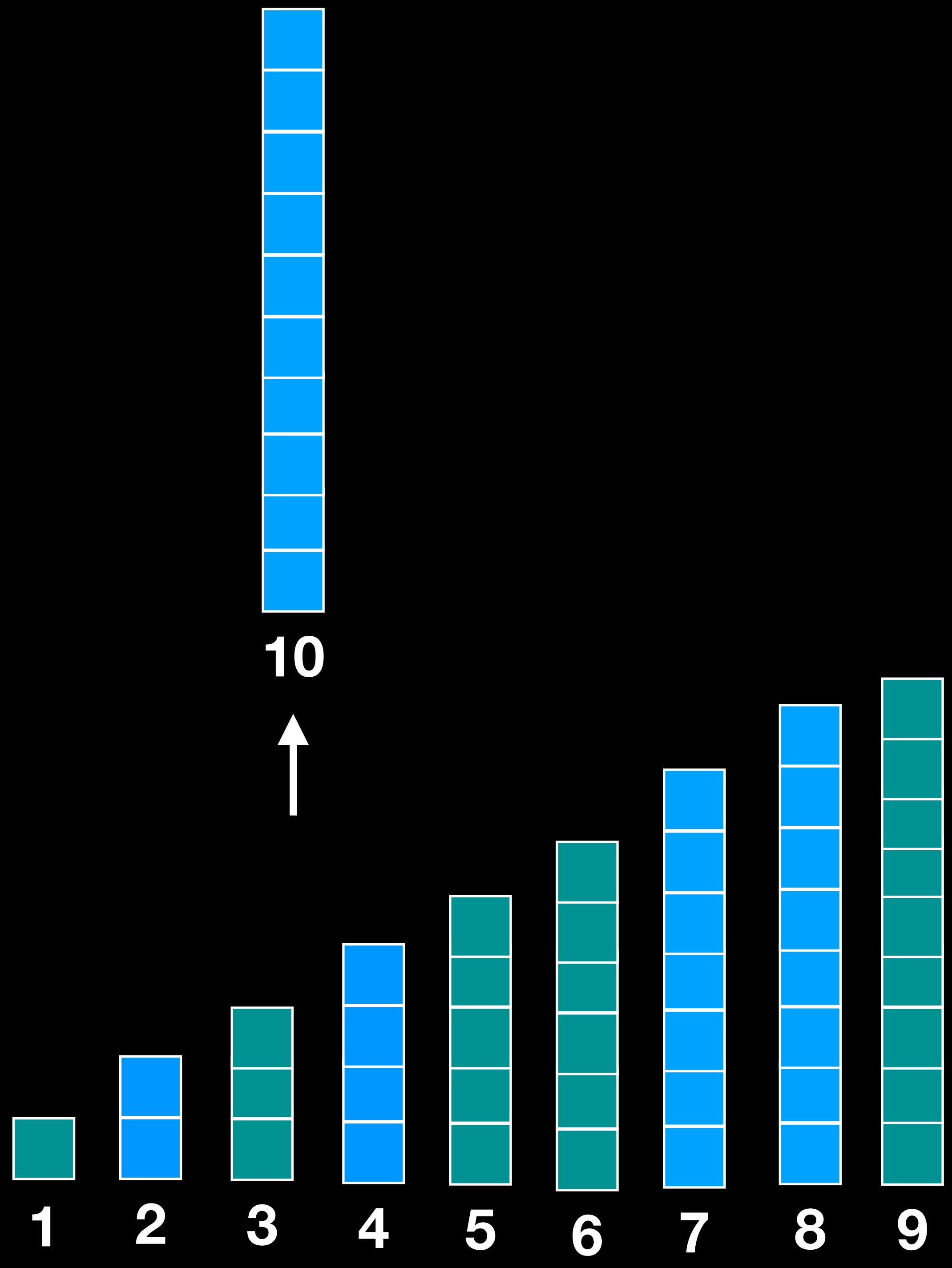
Key Insight: Merge is linear



Key Insight: Merge is linear



Key Insight: Merge is linear



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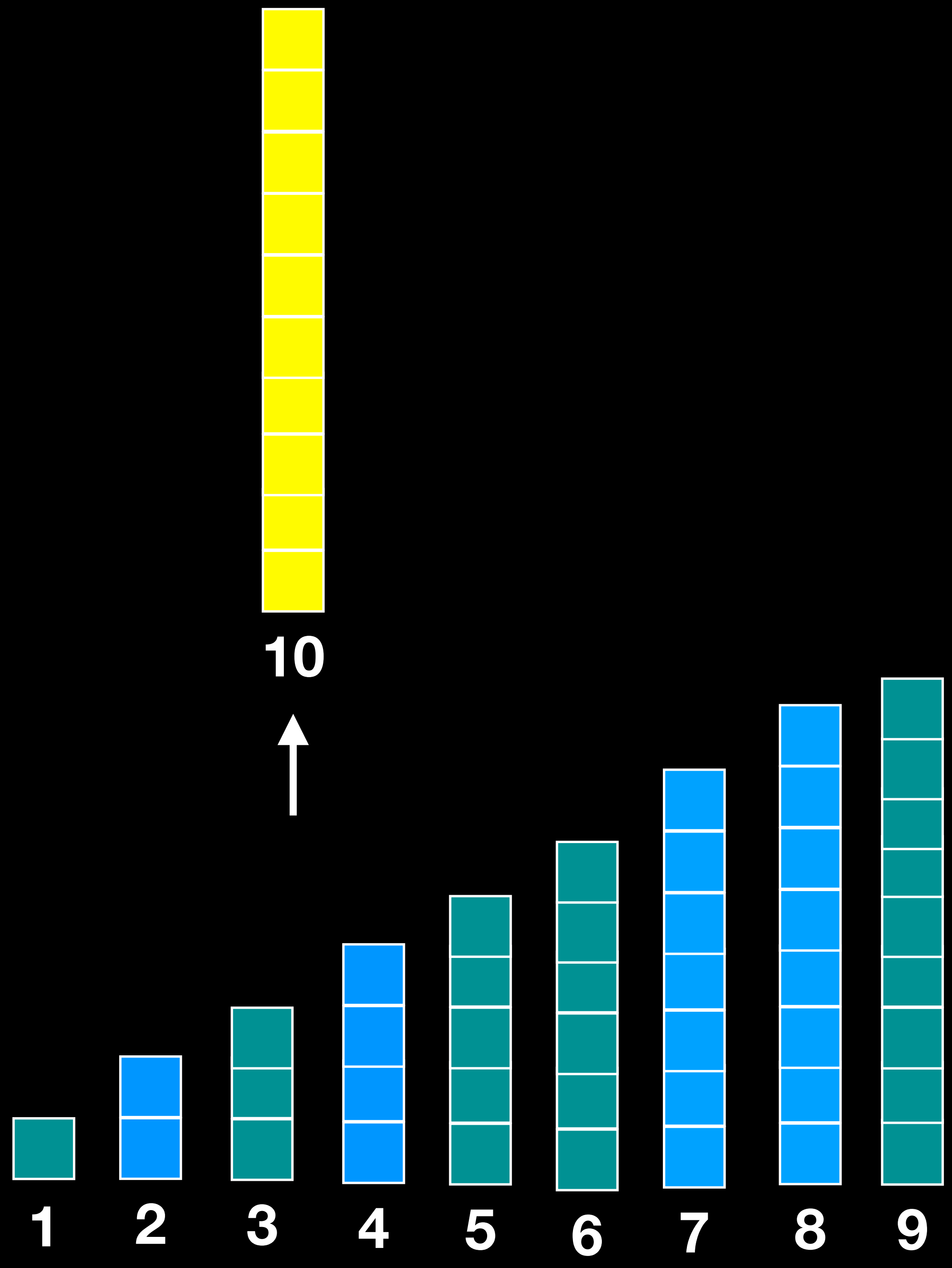
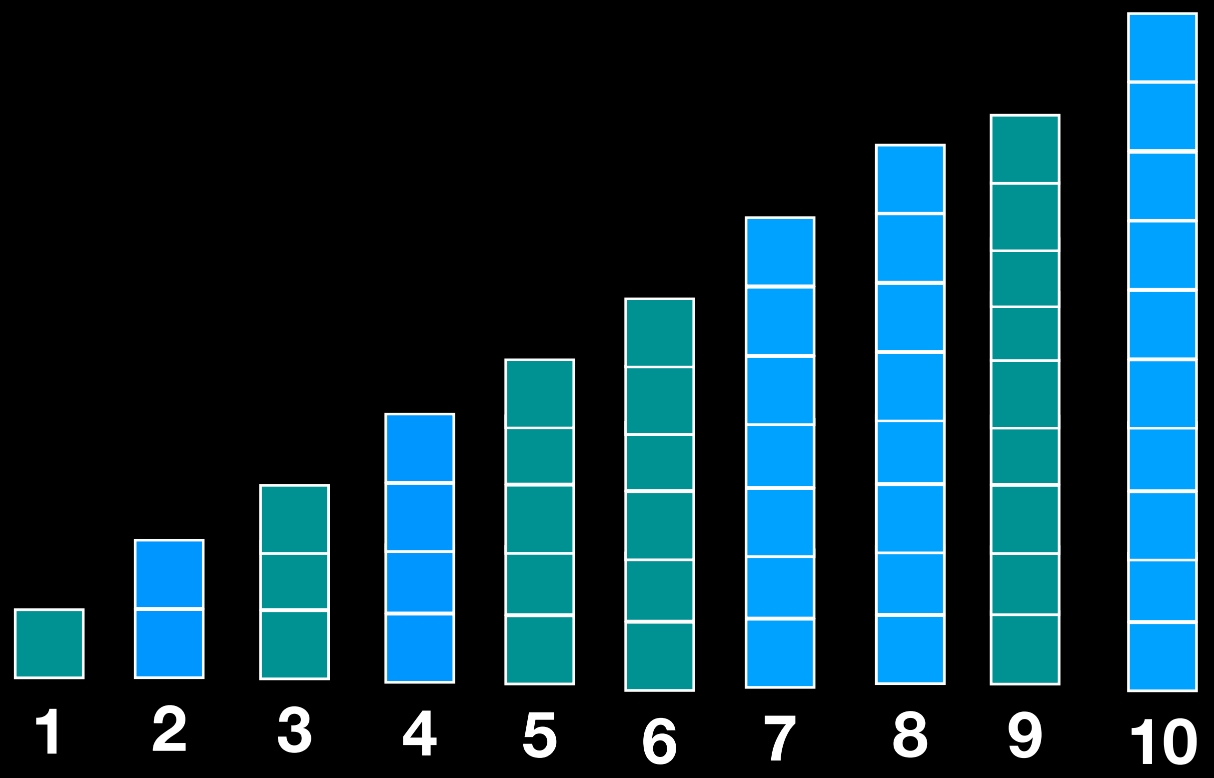
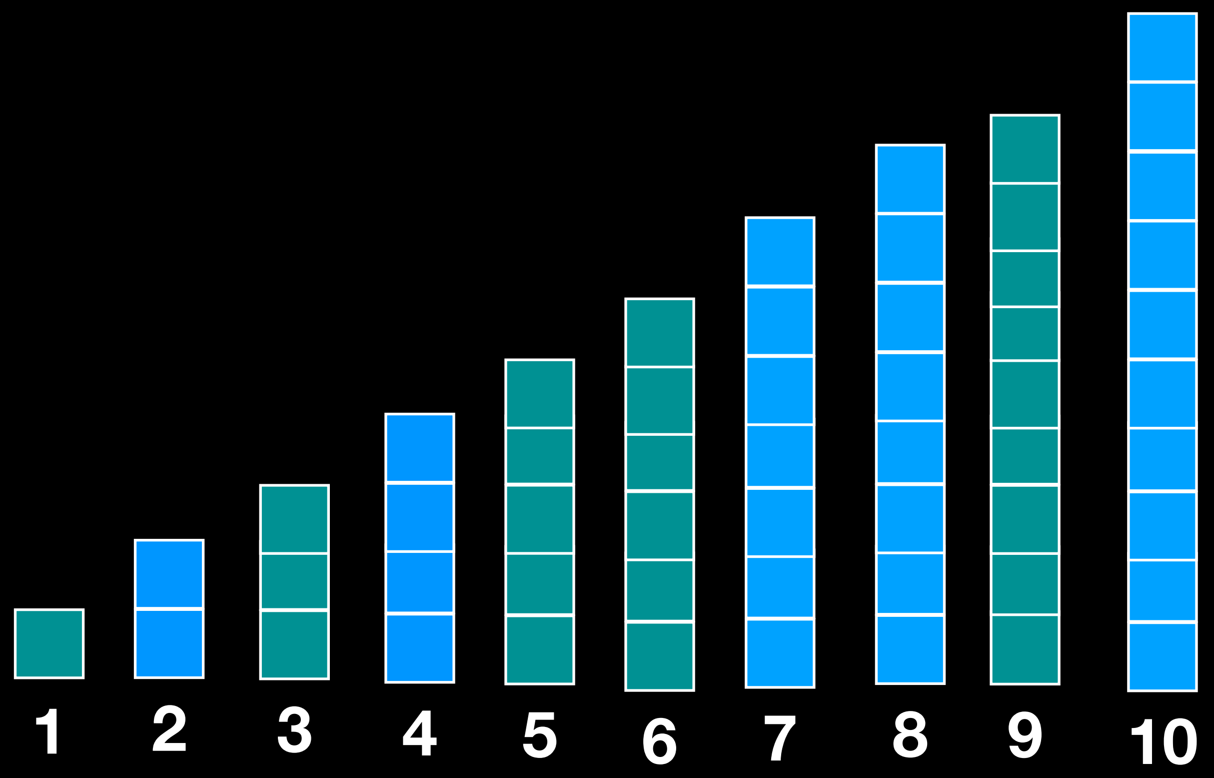


Key Insight: Merge is linear



Key Insight: Merge is linear

Each step makes one comparison and reduces the number of elements to be merged by 1.
If there are *n* total elements to be merged, merging is **O(n)**



Divide and Conquer

100	14	3	43	200	274	523	108	76	195	599	158	2	260	11	64	932	5

$T(n)$

14	43	76	100	108	200	274	523

11	64	158	195	260	599	932

$T(^1/_2 n) \approx {}^1/_4\, T(n)$

$T(^1/_2 n) \approx {}^1/_4\, T(n)$

Divide and Conquer

100	14	3	43	200	274	523	108	76	195	599	158	2	260	11	64	932	5

$T(n)$

14	43	76	100	108	200	274	523

11	64	158	195	260	599	932

$T(^1/_2 n) \approx {}^1/_4\, T(n)$

$T(^1/_2 n) \approx {}^1/_4\, T(n)$

2	3	5	11	14	43	64	76	100	108	158	195	200	260	274	523	599	932

$T(n) \approx {}^1/_2\, T(n) + n$

Speed up insertion sort by a factor of two by splitting in half, sorting separately and merging results!

Divide and Conquer

Splitting in two gives 2x improvement.

Divide and Conquer

Splitting in two gives 2x improvement.

Splitting in four gives 4x improvement.

Divide and Conquer

Splitting in two gives 2x improvement.

Splitting in four gives 4x improvement.

Splitting in eight gives 8x improvement.

Divide and Conquer

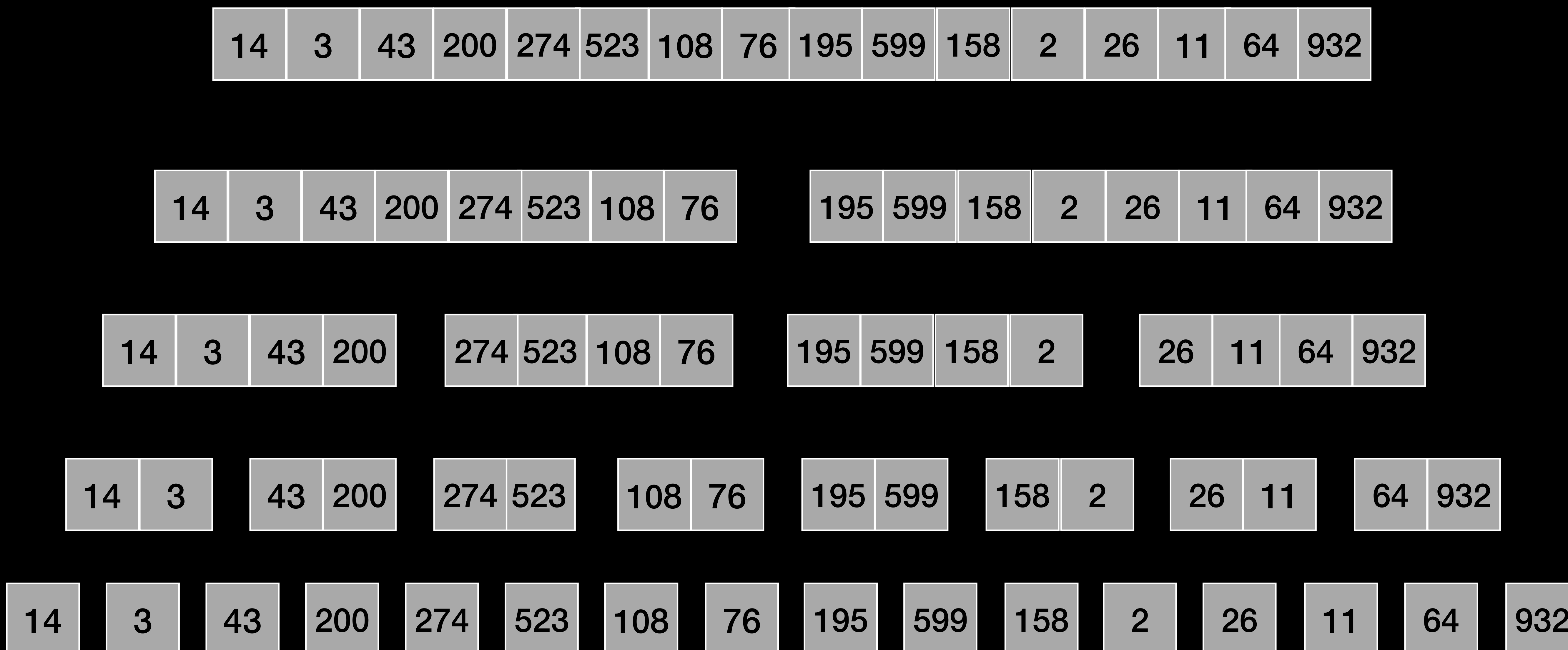
Splitting in two gives 2x improvement.

Splitting in four gives 4x improvement.

Splitting in eight gives 8x improvement.

What if we never stop splitting?

Merge Sort


14 3 43 200 274 523 108 76 195 599 158 2 26 11 64 932
14 3 43 200 274 523 108 76
195 599 158 2 26 11 64 932
14 3 43 200
274 523 108 76
195 599 158 2
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14 3
43 200
274 523
108 76
195 599
158 2
26 11
64 932
14
3
43
200
274
523
108
76
195
599
158
2
26
11
64
932

Merge Sort


14 3 43 200 274 523 108 76 195 599 158 2 26 11 64 932
14 3 43 200 274 523 108 76
195 599 158 2 26 11 64 932
14 3 43 200
274 523 108 76
195 599 158 2
26 11 64 932
14 3
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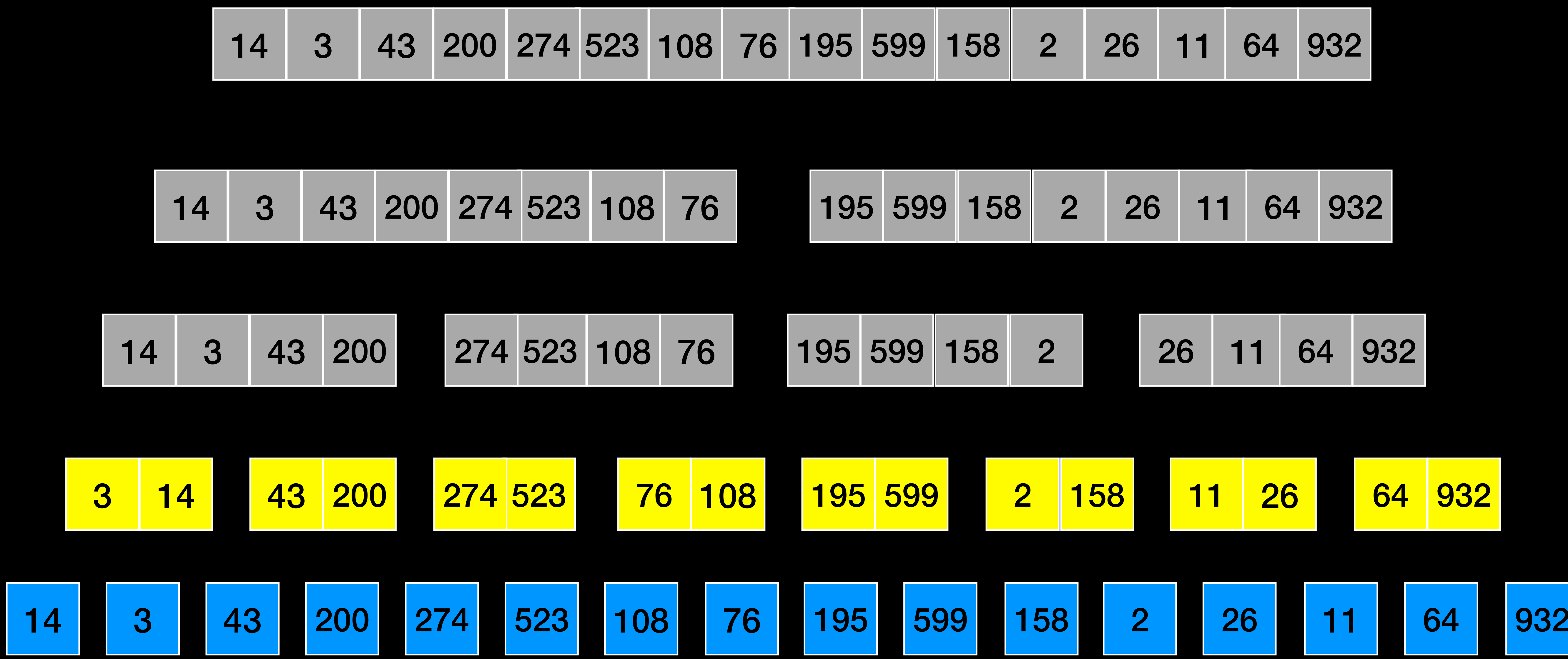
274 523
108 76
195 599
158 2
26 11
64 932
14 3 43 200 274 523 108 76 195 599 158 2 26 11 64 932

Merge Sort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3 14
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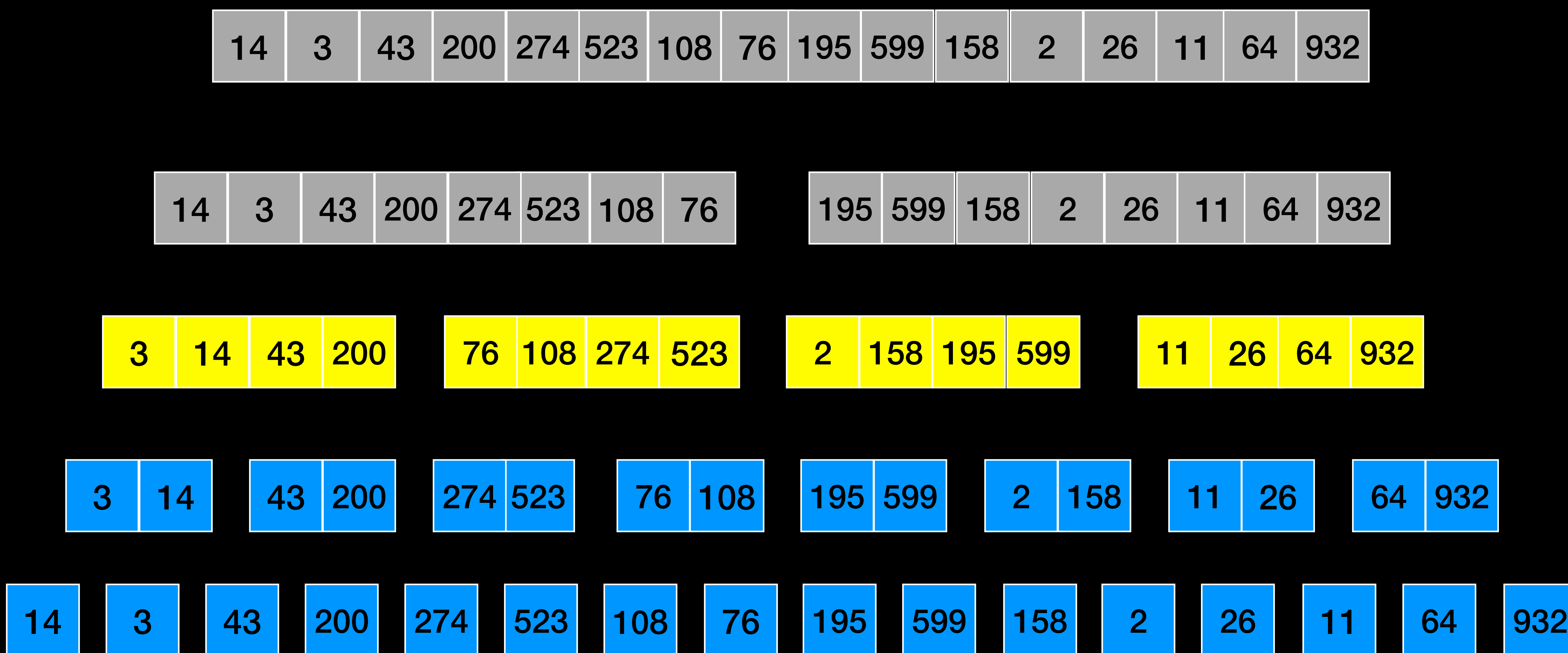
274 523
76 108
195 599
2 158
11 26
64 932
14 3 43 200 274 523 108 76 195 599 158 2 26 11 64 932

Merge Sort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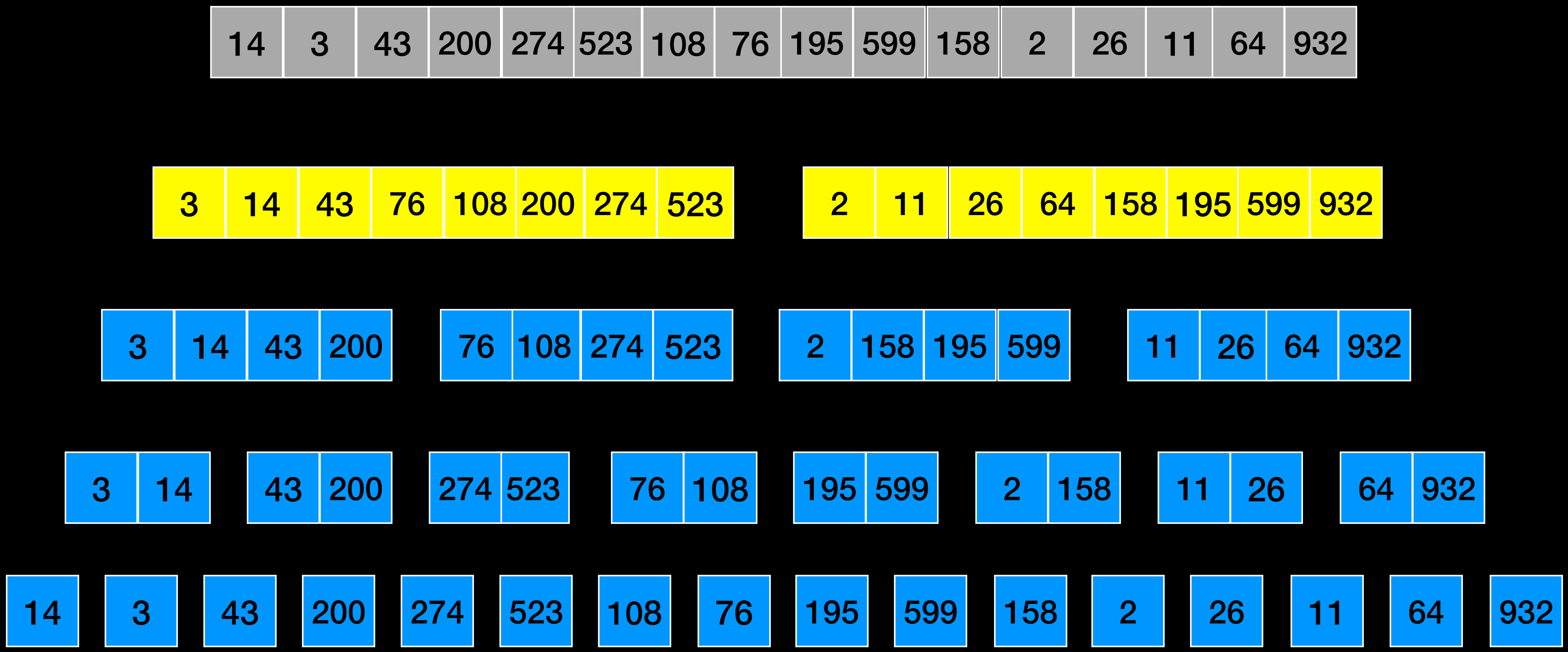
Merge Sort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3 14 43 76 108 200 274 523
2 11 26 64 158 195 599 932
3 14 43 200
76 108 274 523
2 158 195 599
11 26 64 932
3 14
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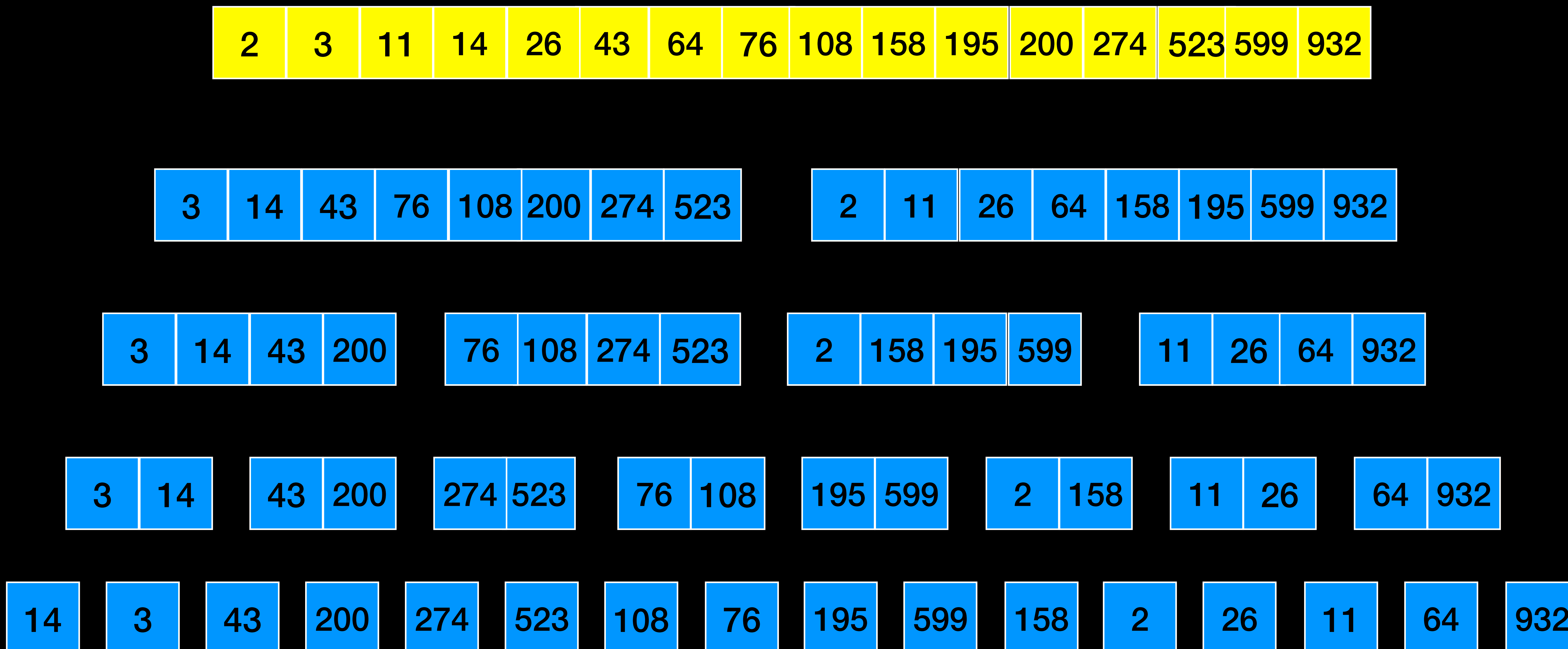
274 523
76 108
195 599
2 158
11 26
64 932
14 3 43 200 274 523 108 76 195 599 158 2 26 11 64 932

Merge Sort



2 3 11 14 26 43 64 76 108 158 195 200 274 523 599 932
3 14 43 76 108 200 274 523
2 11 26 64 158 195 599 932
3 14 43 200
76 108 274 523
2 158 195 599
11 26 64 932
3 14
43 200
274 523
76 108
195 599
2 158
11 26
64 932
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3
43
200
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108
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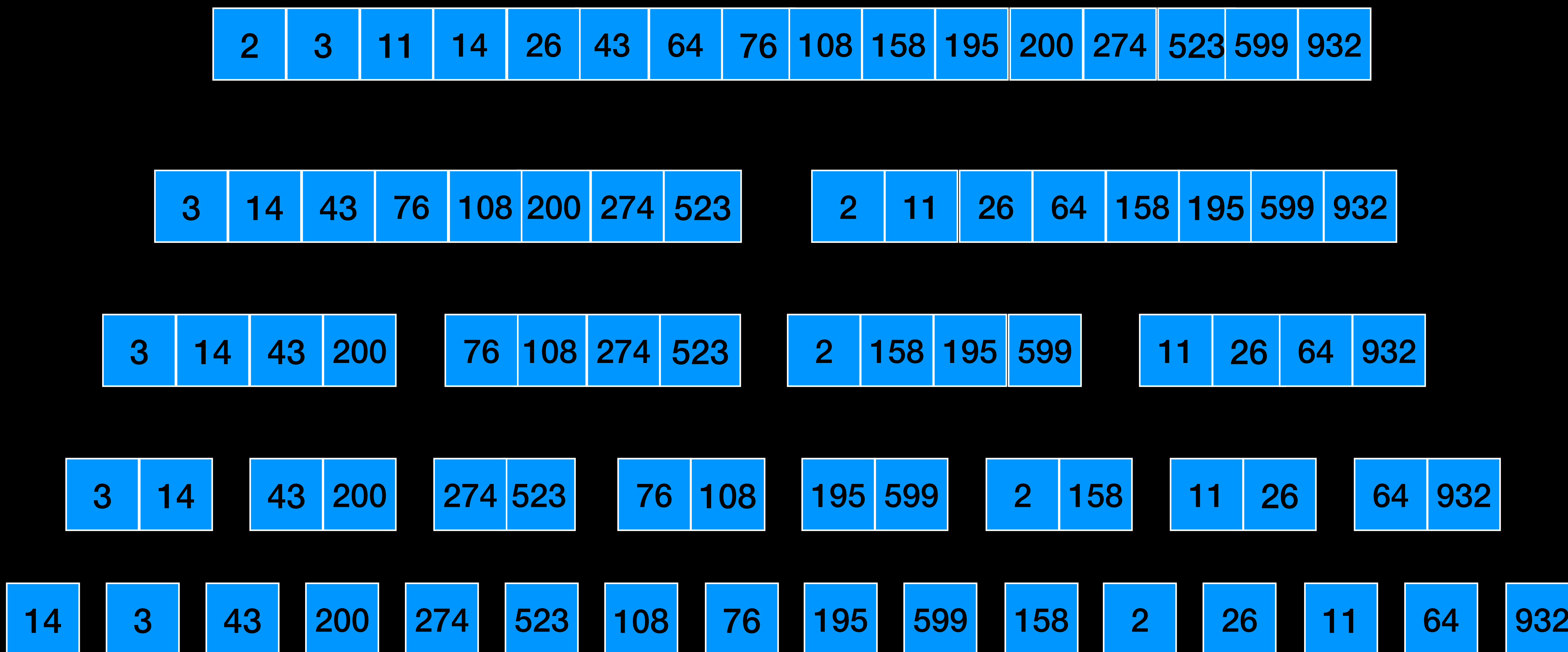
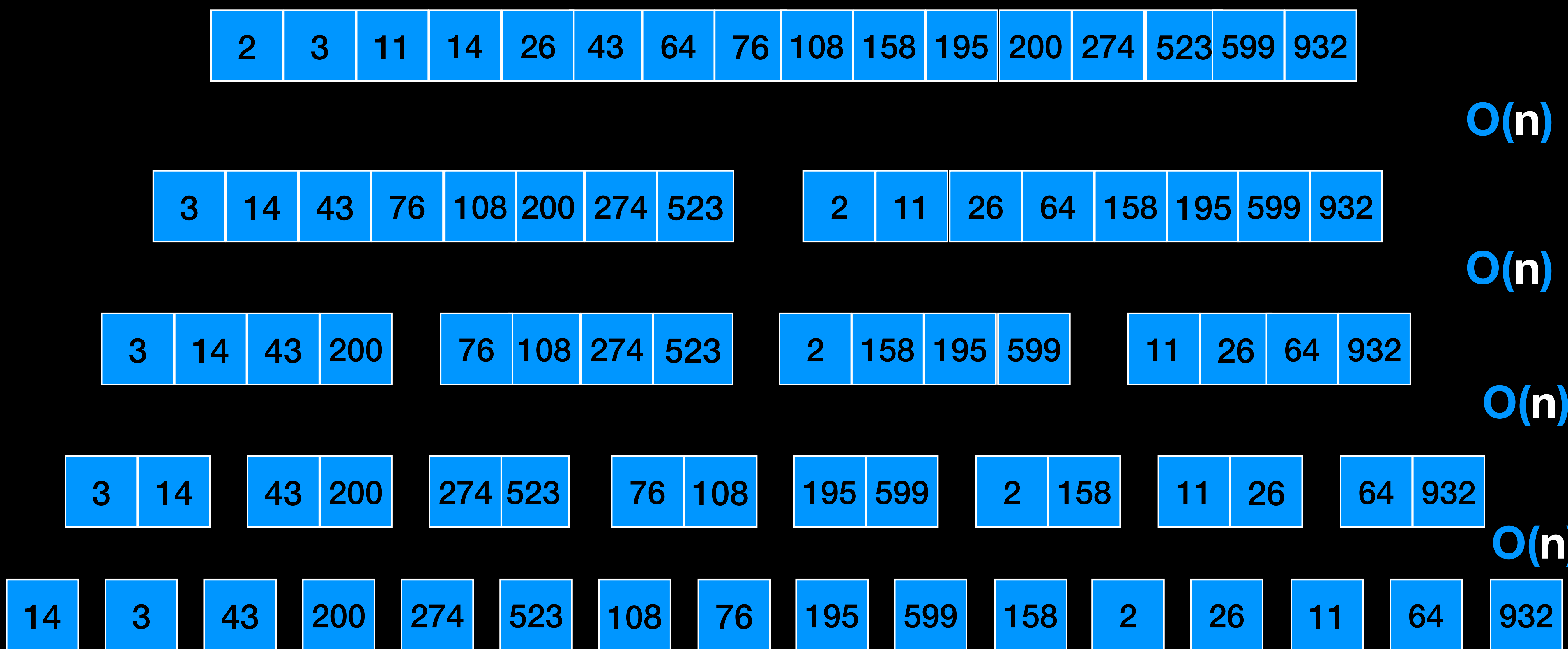
195
599
158
2
26
11
64
932

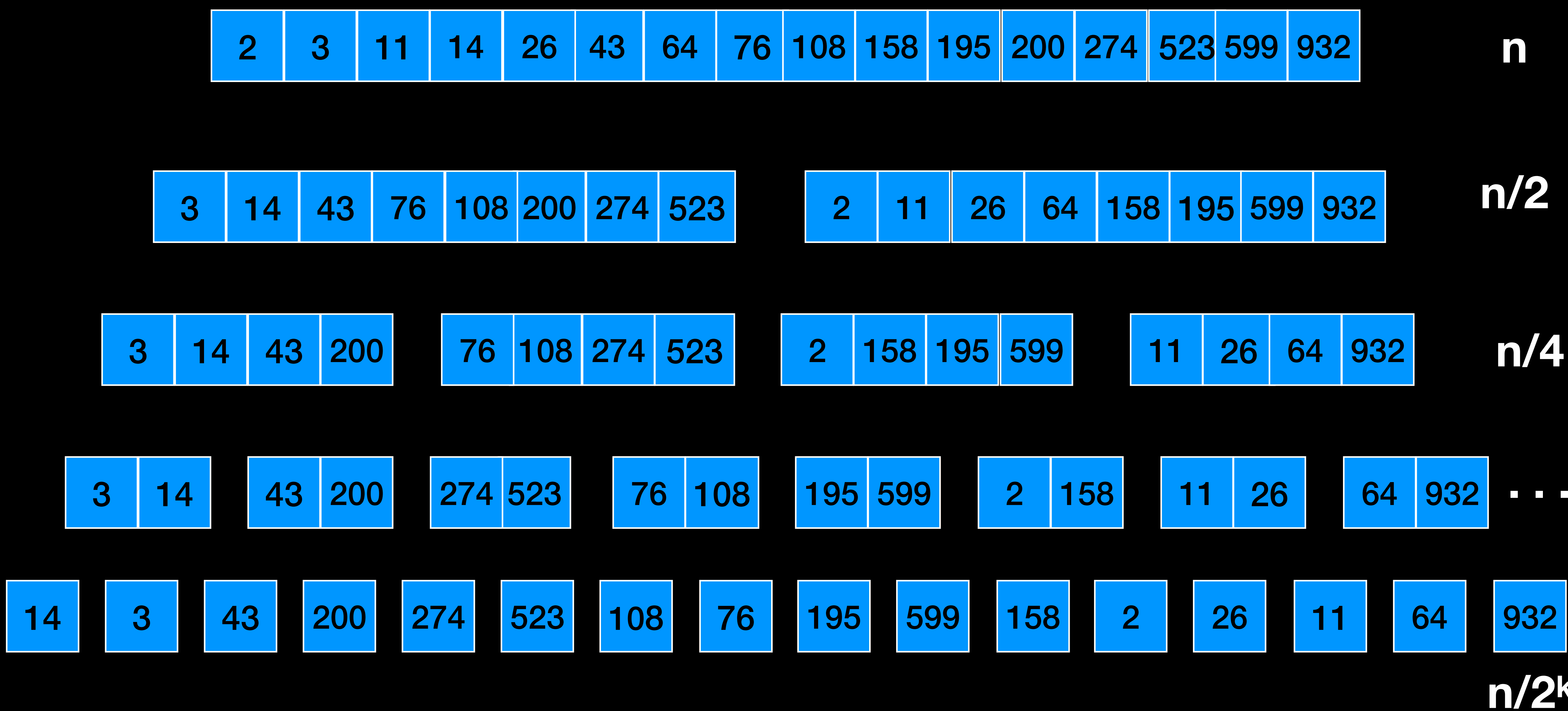
Merge Sort


2 3 11 14 26 43 64 76 108 158 195 200 274 523 599 932
3 14 43 76 108 200 274 523
2 11 26 64 158 195 599 932
3 14 43 200
76 108 274 523
2 158 195 599
11 26 64 932
3 14
43 200
274 523
76 108
195 599
2 158
11 26
64 932
14 3 43 200 274 523 108 76 195 599 158 2 26 11 64 932

Merge Sort Analysis

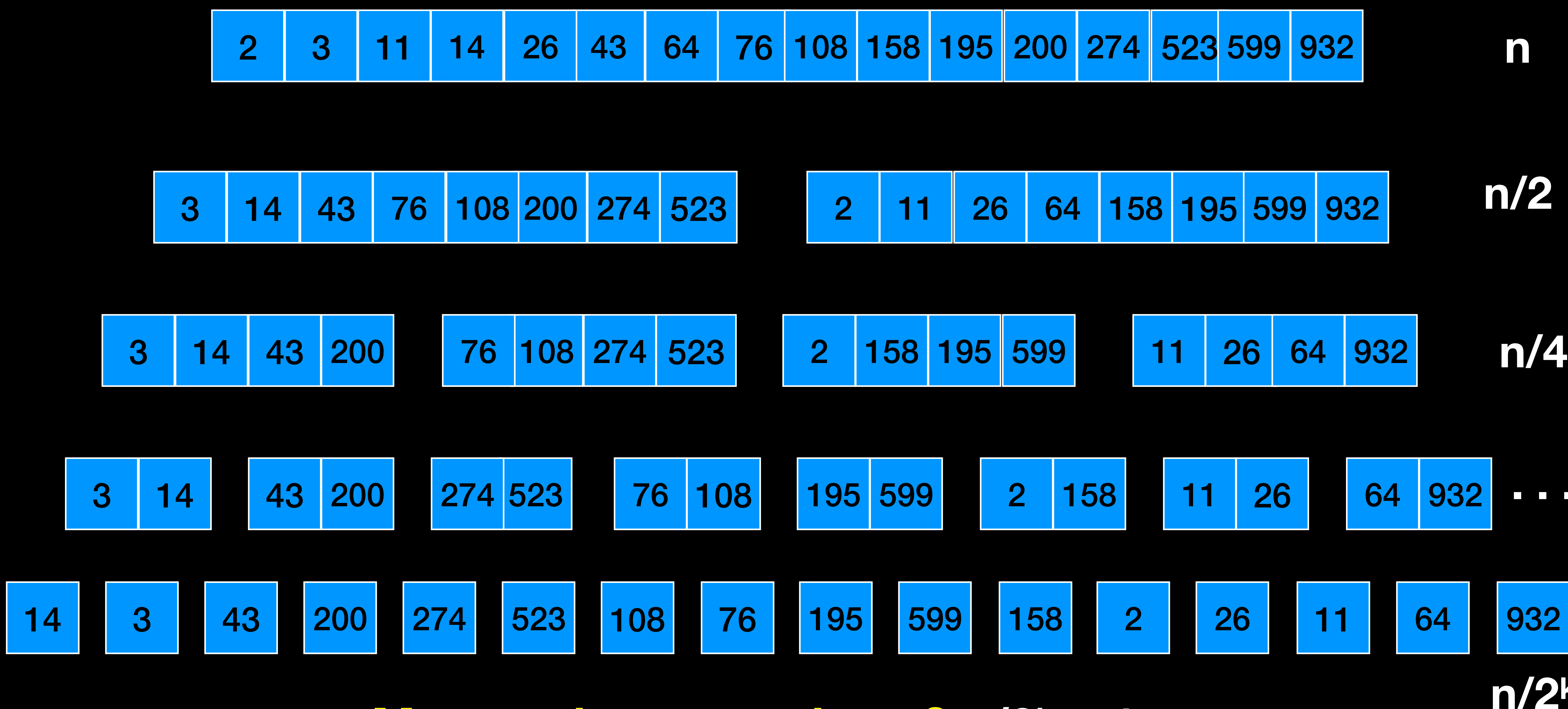


Merge Sort Analysis



Merge n how many times?

Merge Sort Analysis

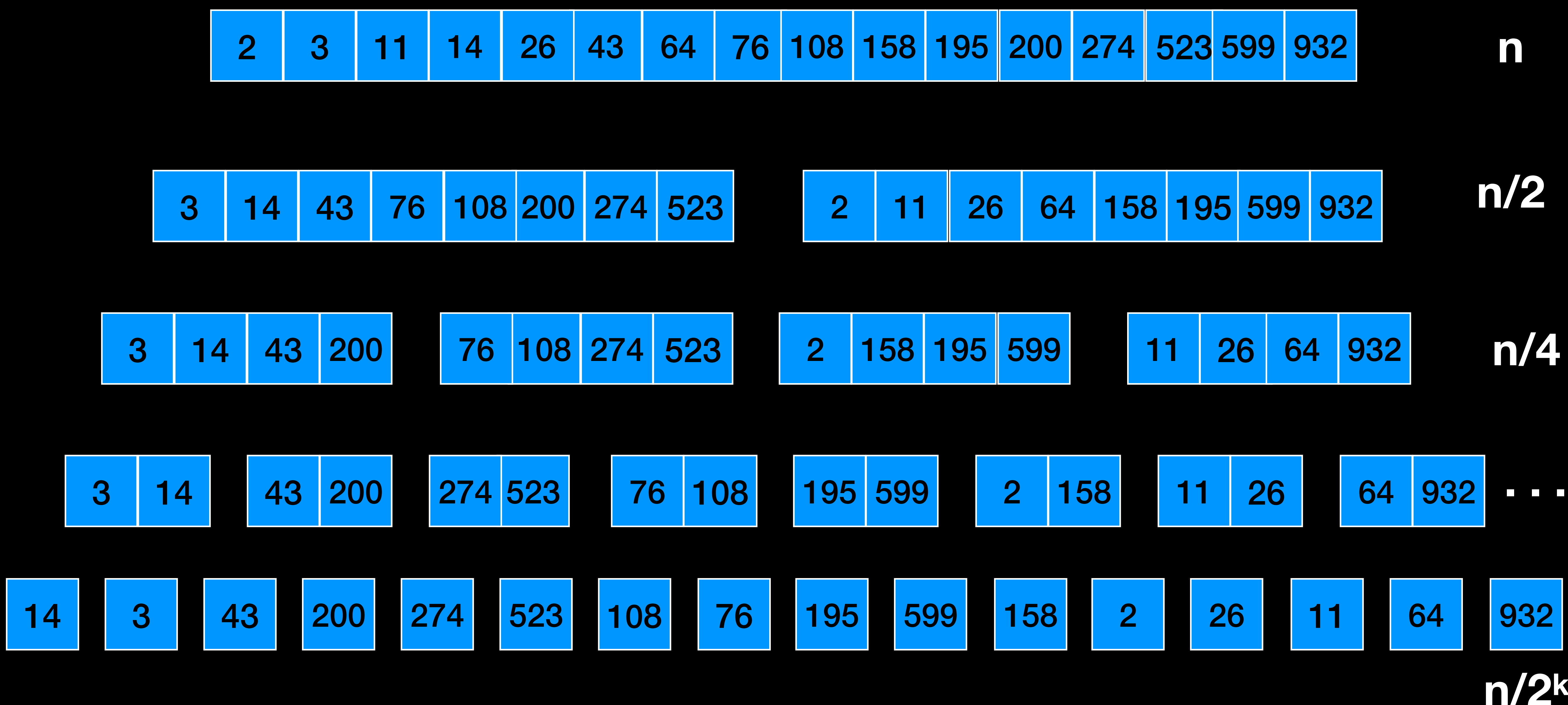


Merge n how may times? $n/2^k = 1$

$n = 2^k$

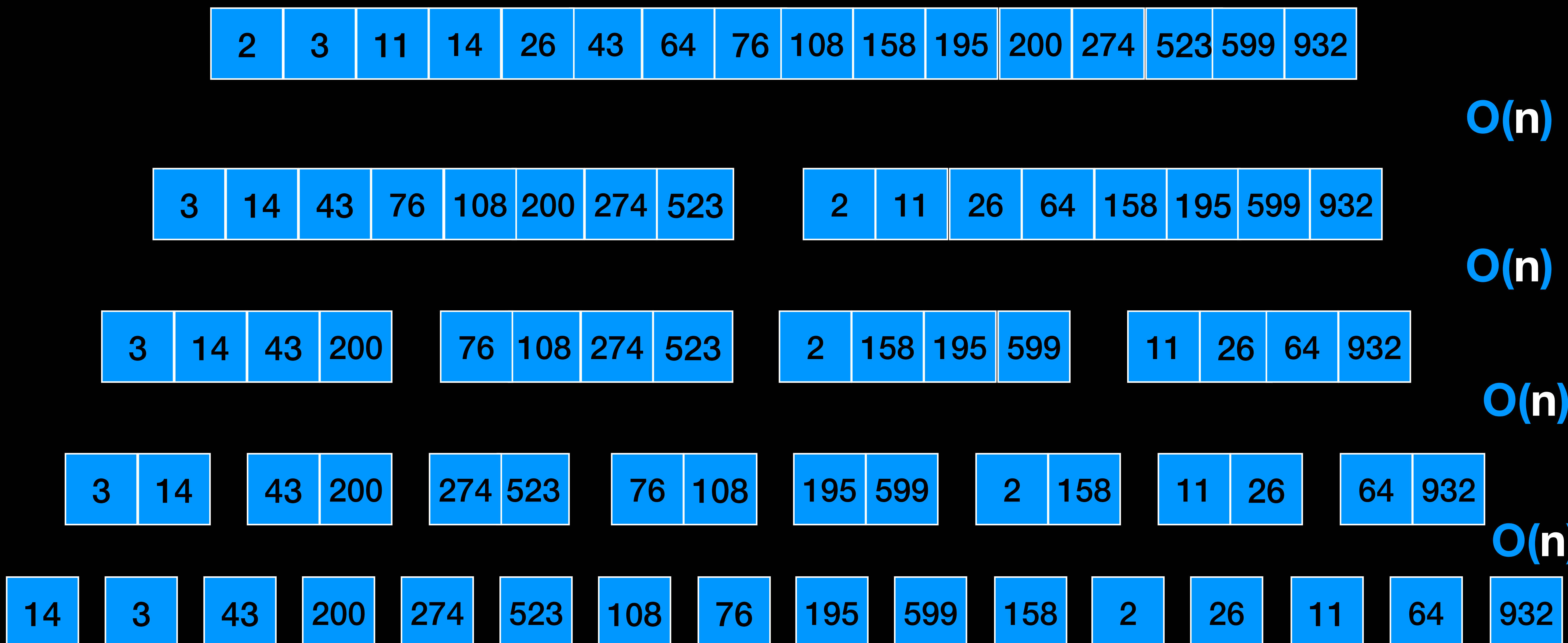
$\log_2 n = k$

Merge Sort Analysis



Merge n elements $\log_2 n$ times

Merge Sort Analysis



O(n log n)

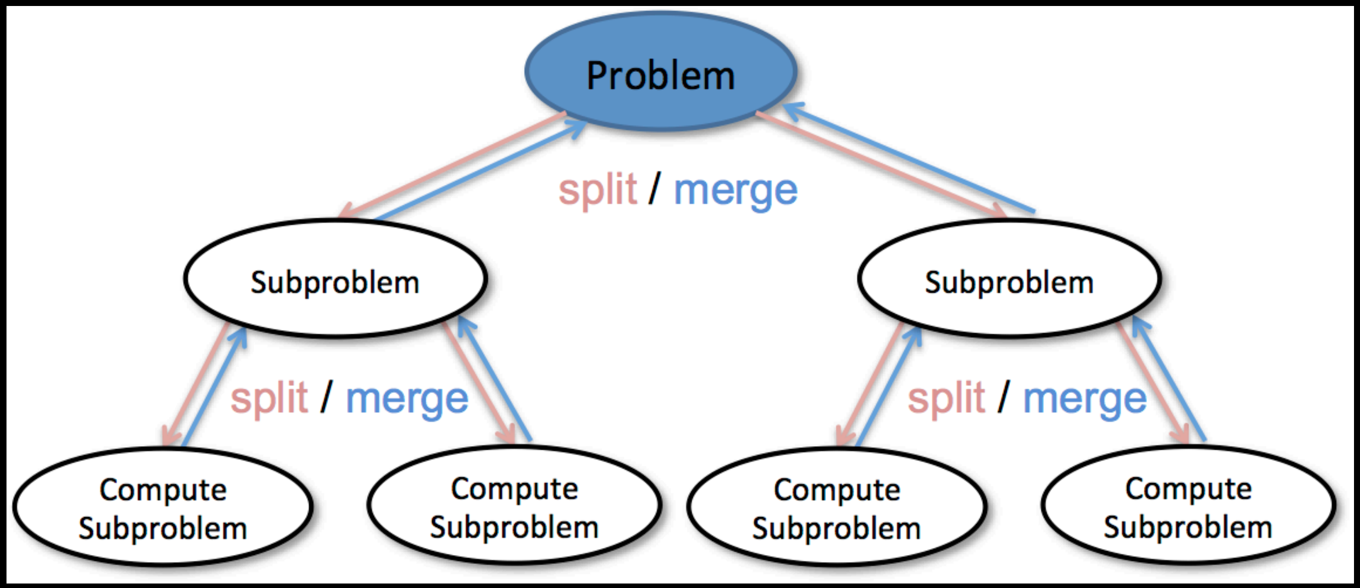
Merge Sort

How would you code this?

Merge Sort

How would you code this?

Hint: Divide and Conquer!!!



Merge Sort

```
Vector mergeSort(array)
{
    if array size <= 1
        return  array //base case
    split array into left_array and right_array
    mergeSort(left_array)
    mergeSort(right_array)

    array = merge(left_array, right_array)
    return array
}
```

Now sorted: contains left and right merged

Merge Sort Analysis

Execution time does NOT depend on initial arrangement of data

Worst Case: O(n log n) comparisons and data moves

Best Case: O(n log n) comparisons and data moves

Stable

Best we can do with *comparison-based* sorting that does not rely on a data structure in the worst case => can't beat O(n log n)

Space overhead: auxiliary array at each merge step

What we have so far

	Worst Case	Best Case
Selection Sort	$O(n^2)$	$O(n^2)$
Insertion Sort	$O(n^2)$	$O(n)$
Bubble Sort	$O(n^2)$	$O(n)$
Merge Sort	$O(n \log n)$	$O(n \log n)$

Quick Sort

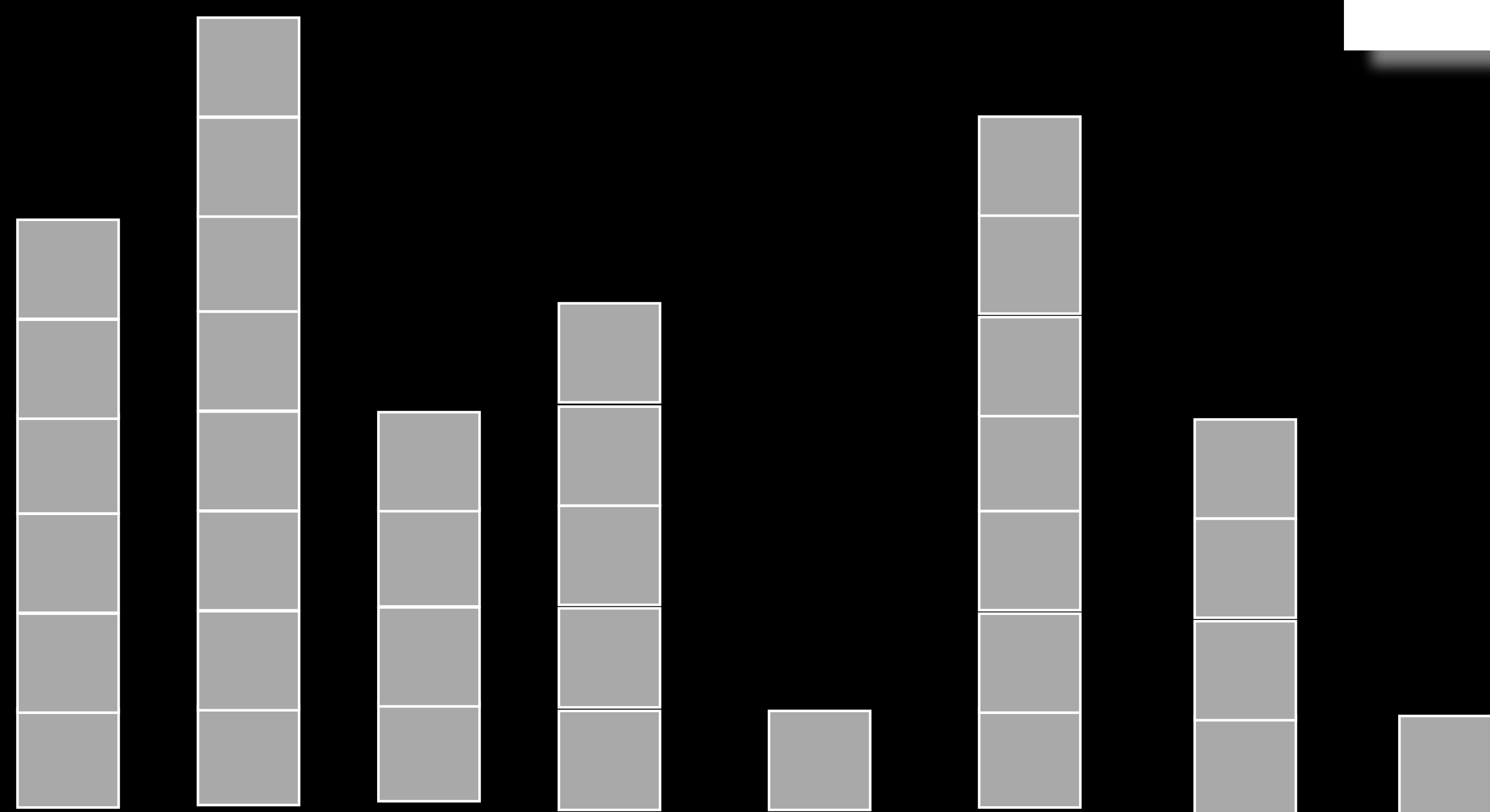
Quick Sort

Select a **pivot.** Arrange other entries s.t. entries in left partition are ≤ pivot and entries in right partition are > pivot

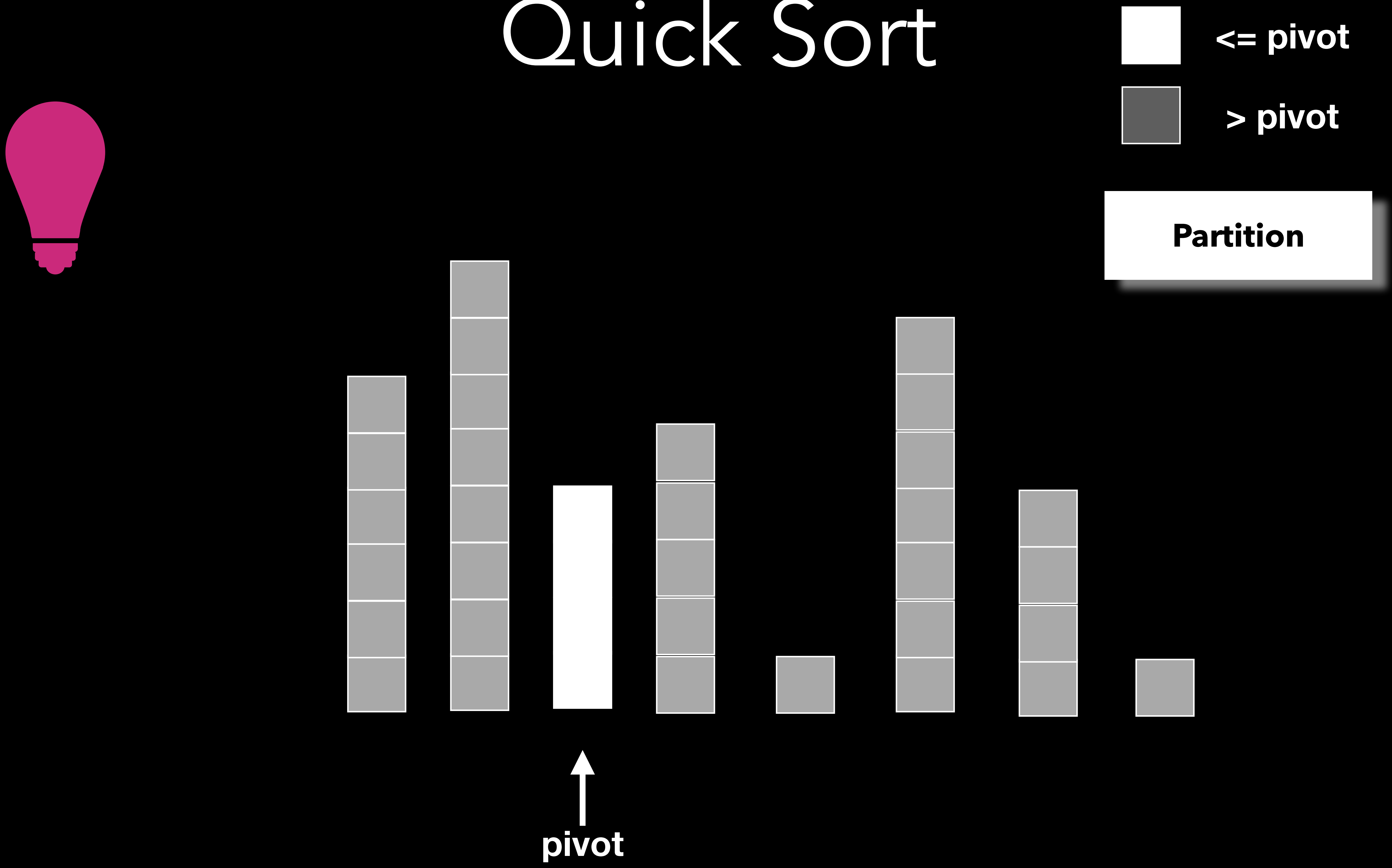
<= pivot

> pivot

Partition



Quick Sort



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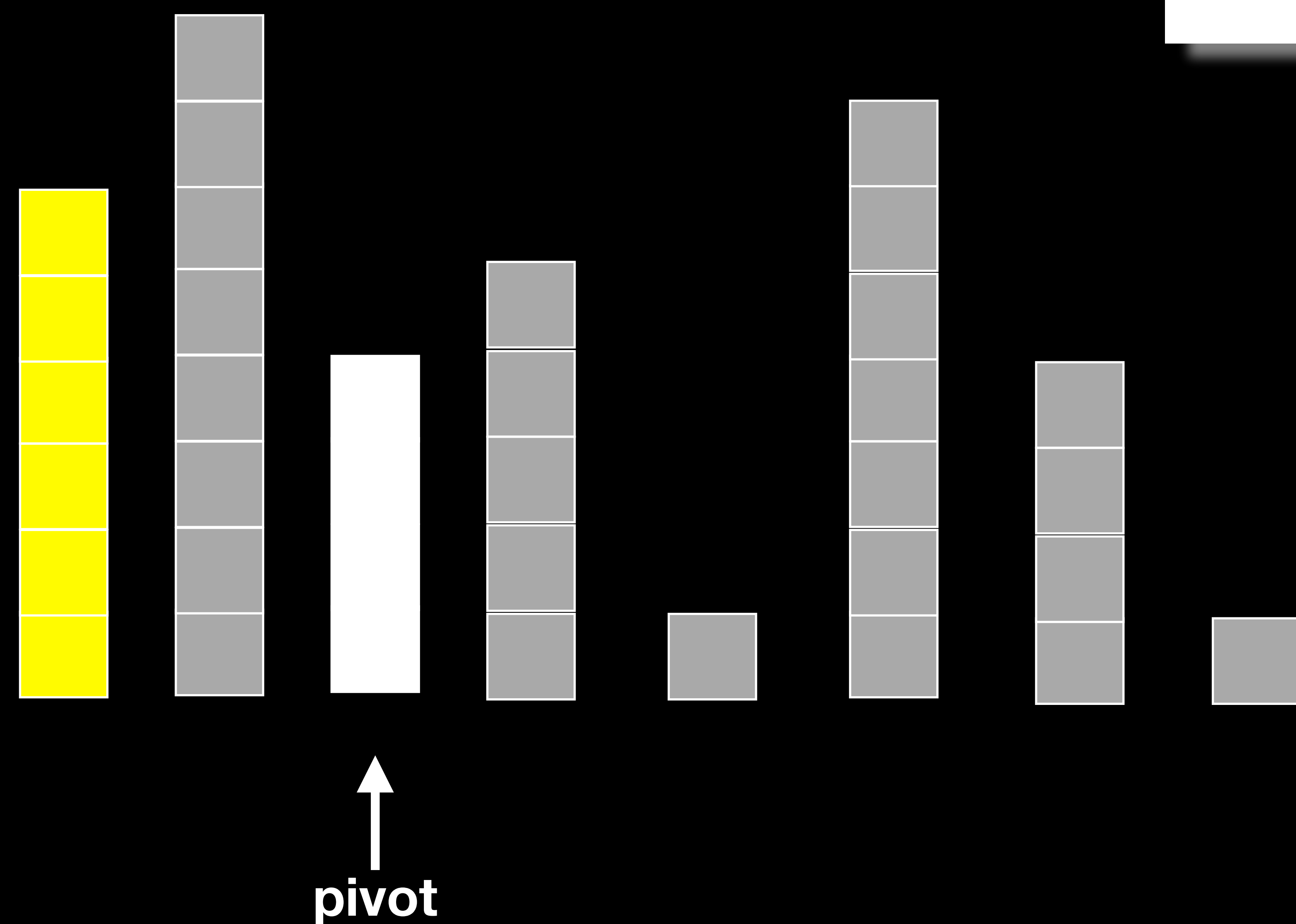

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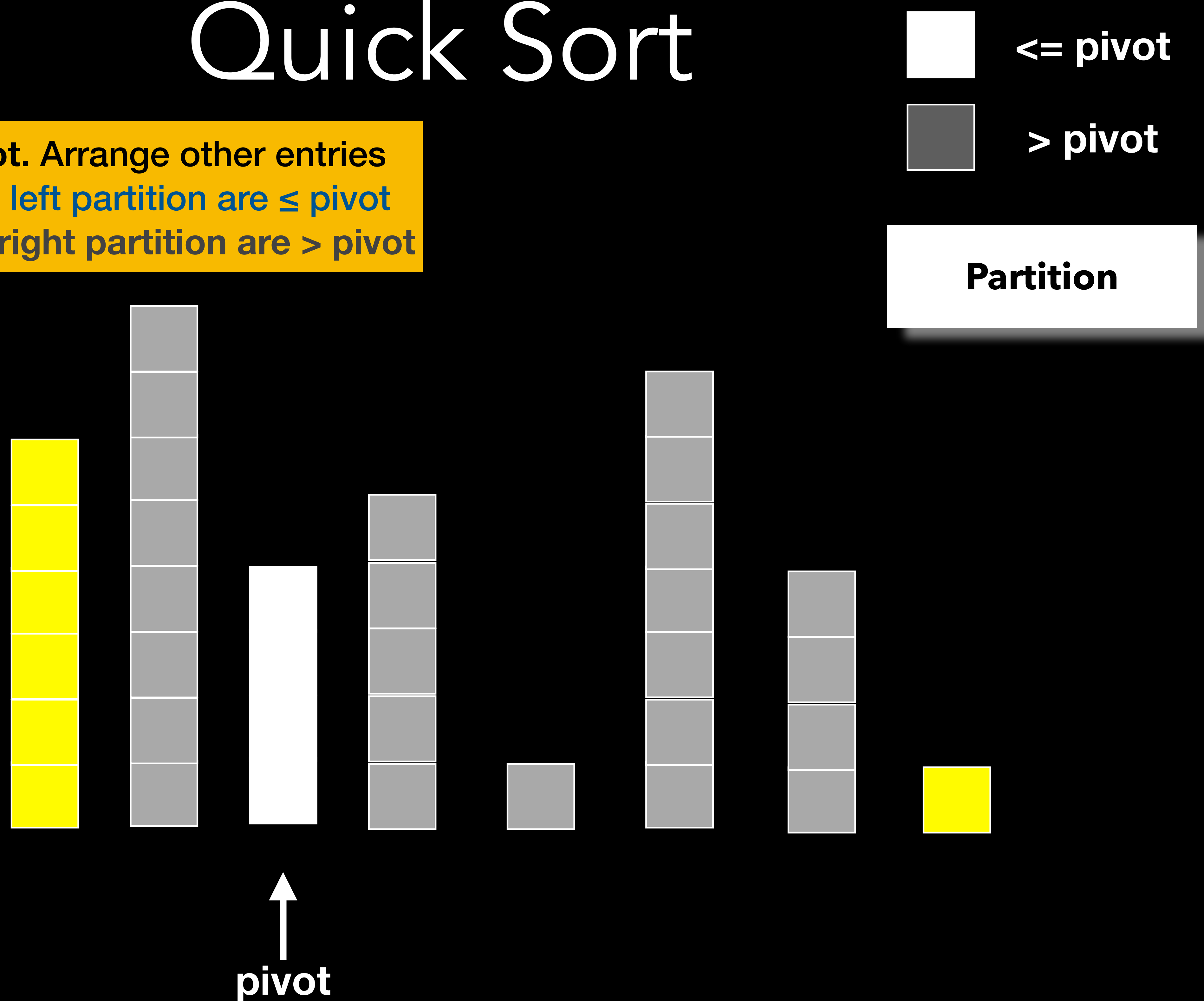

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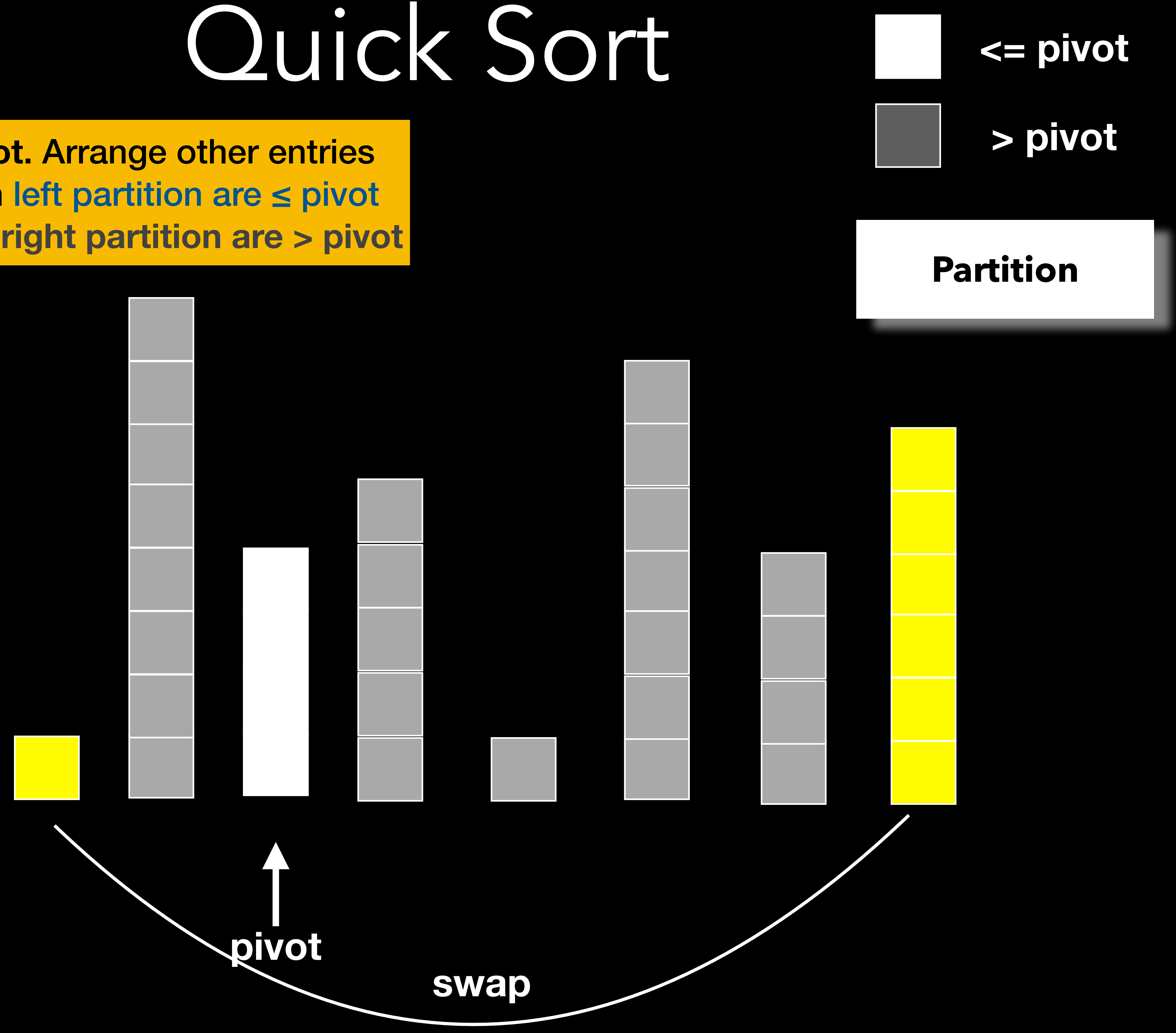

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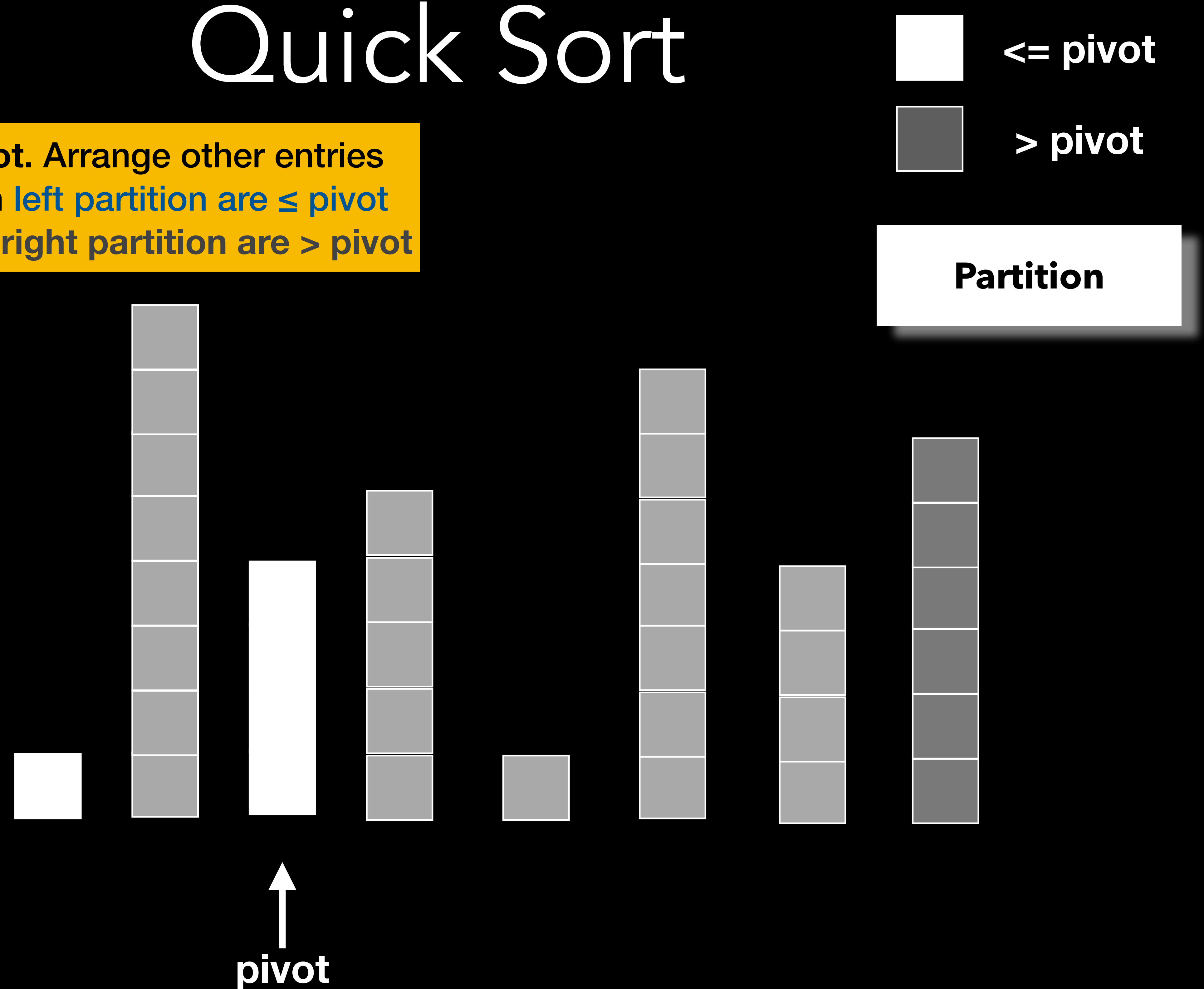

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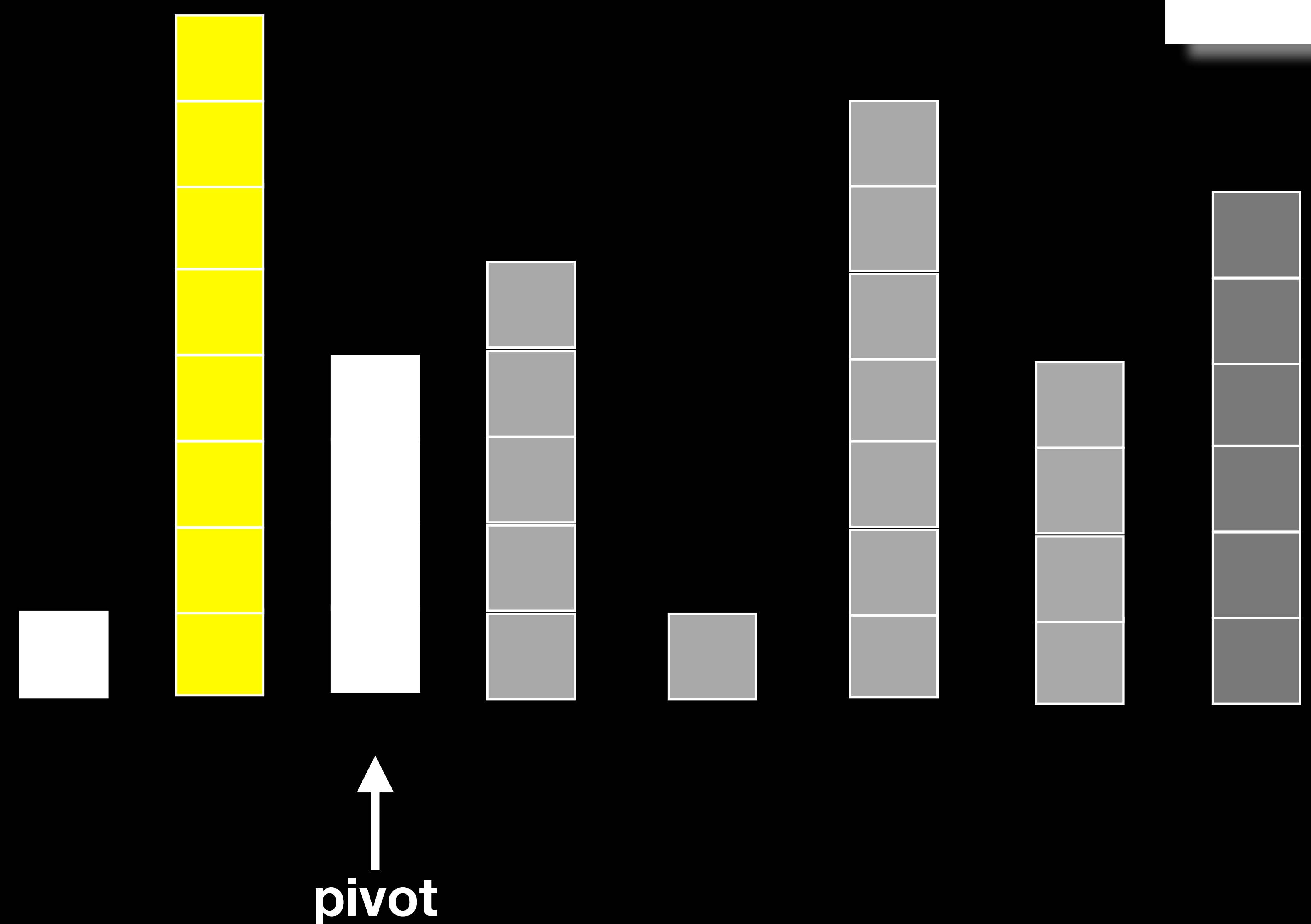

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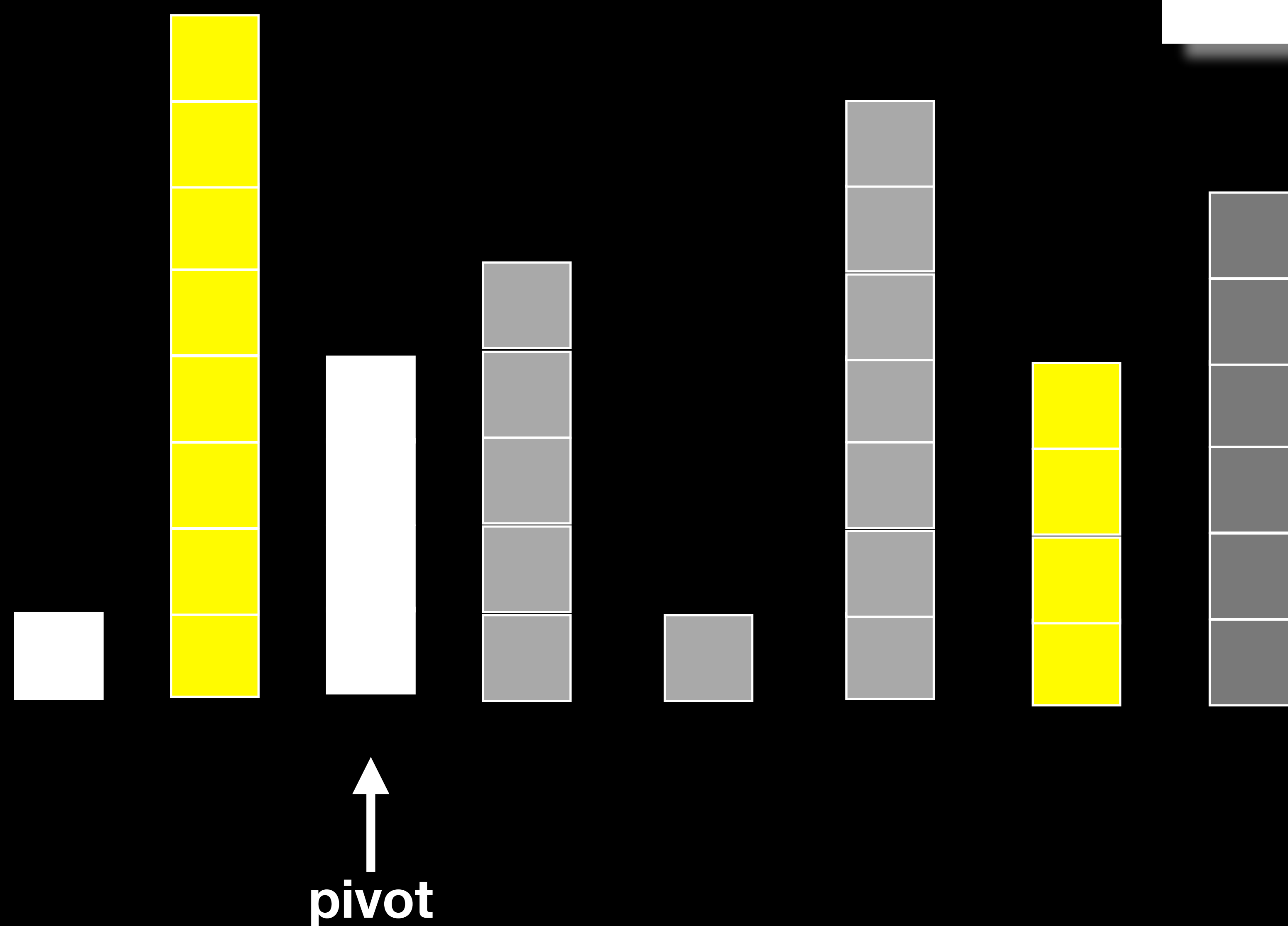

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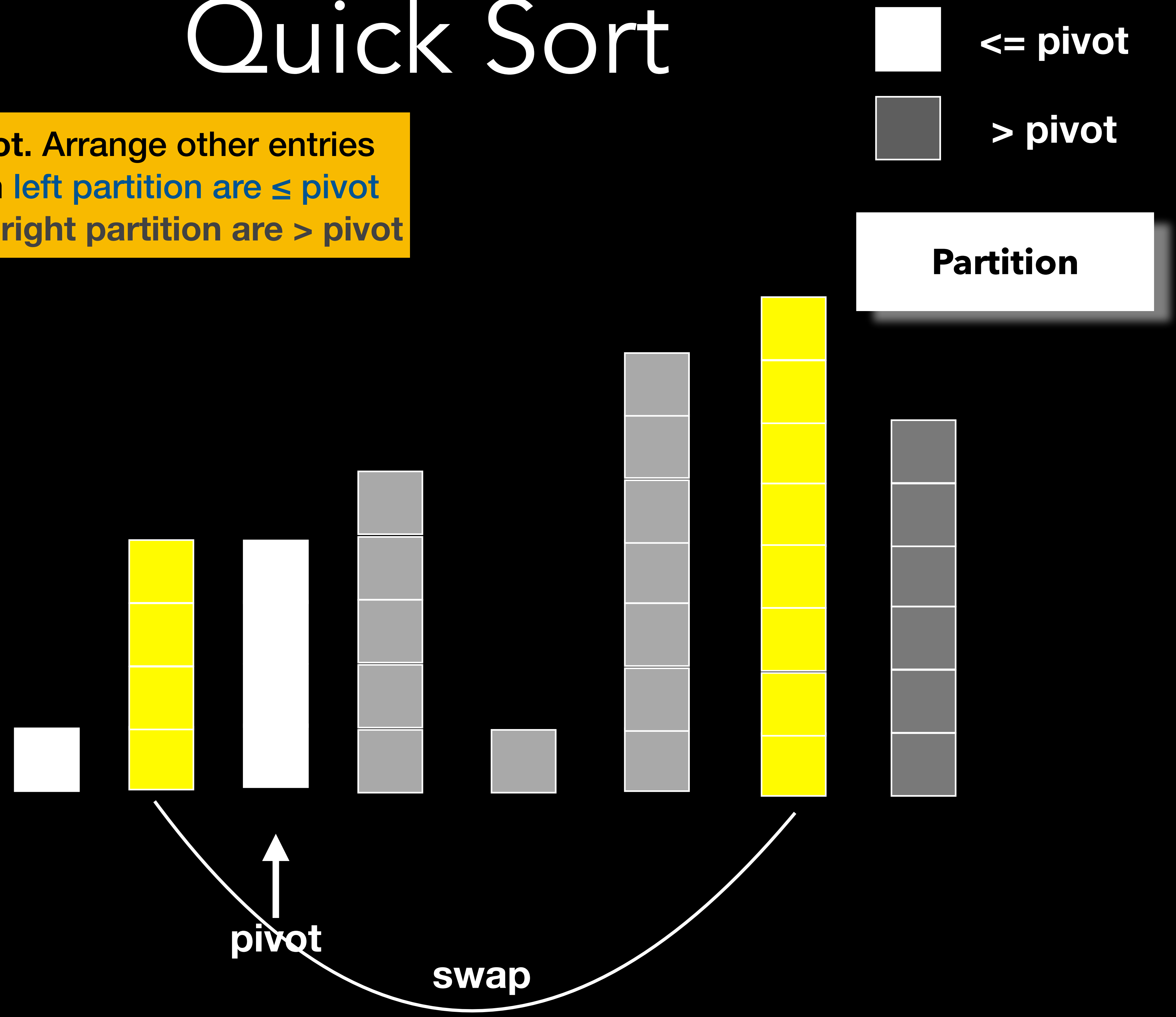

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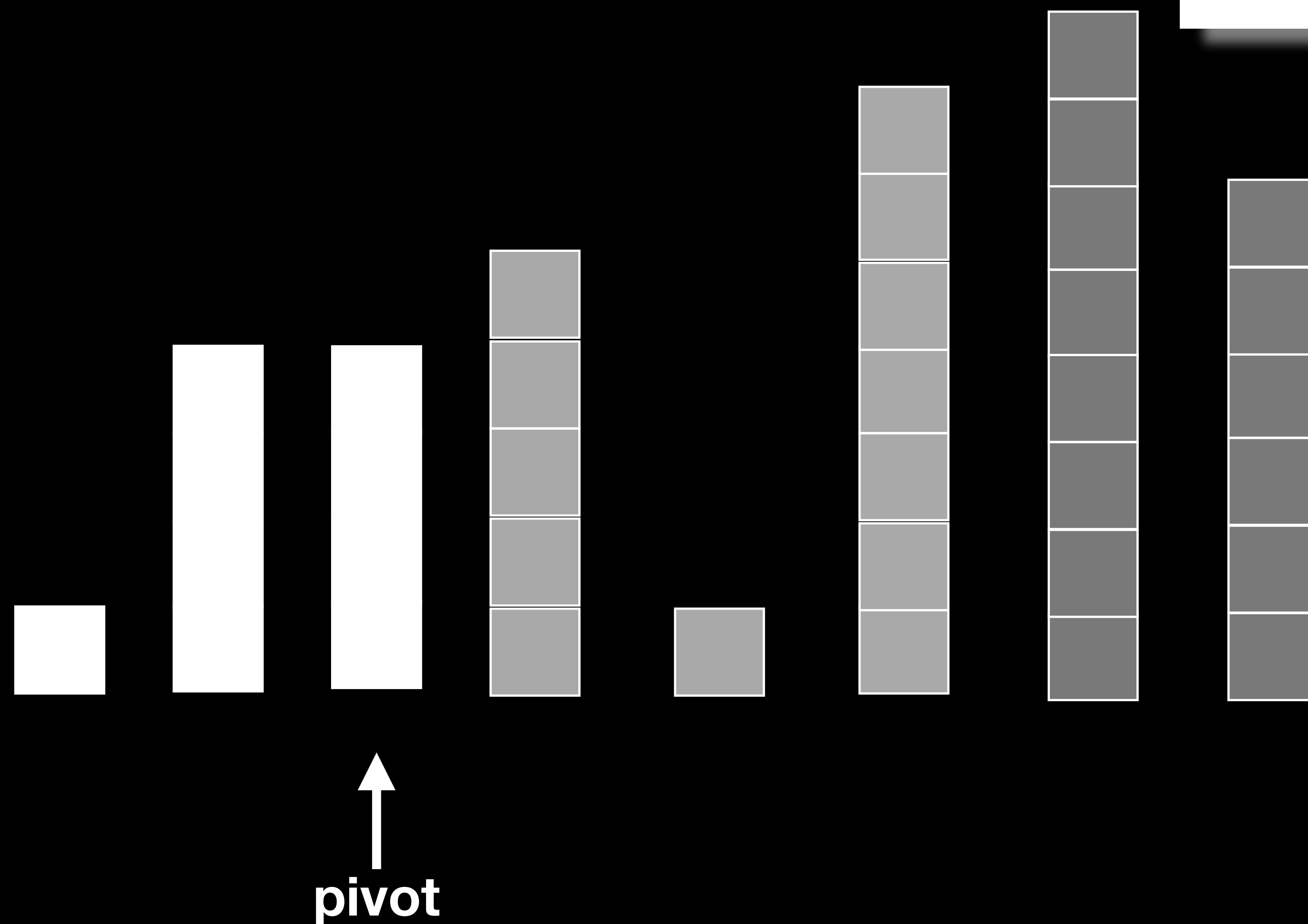

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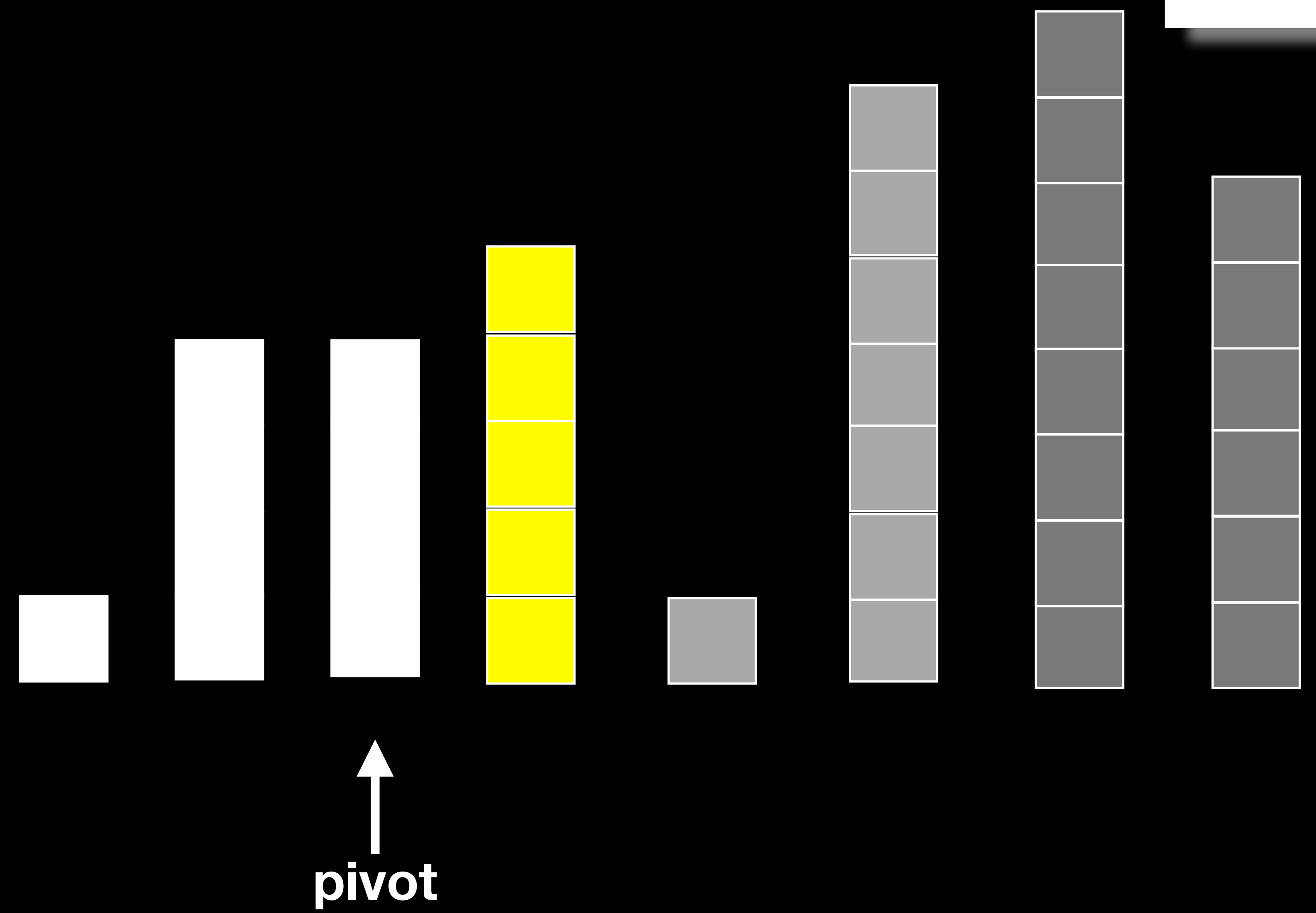

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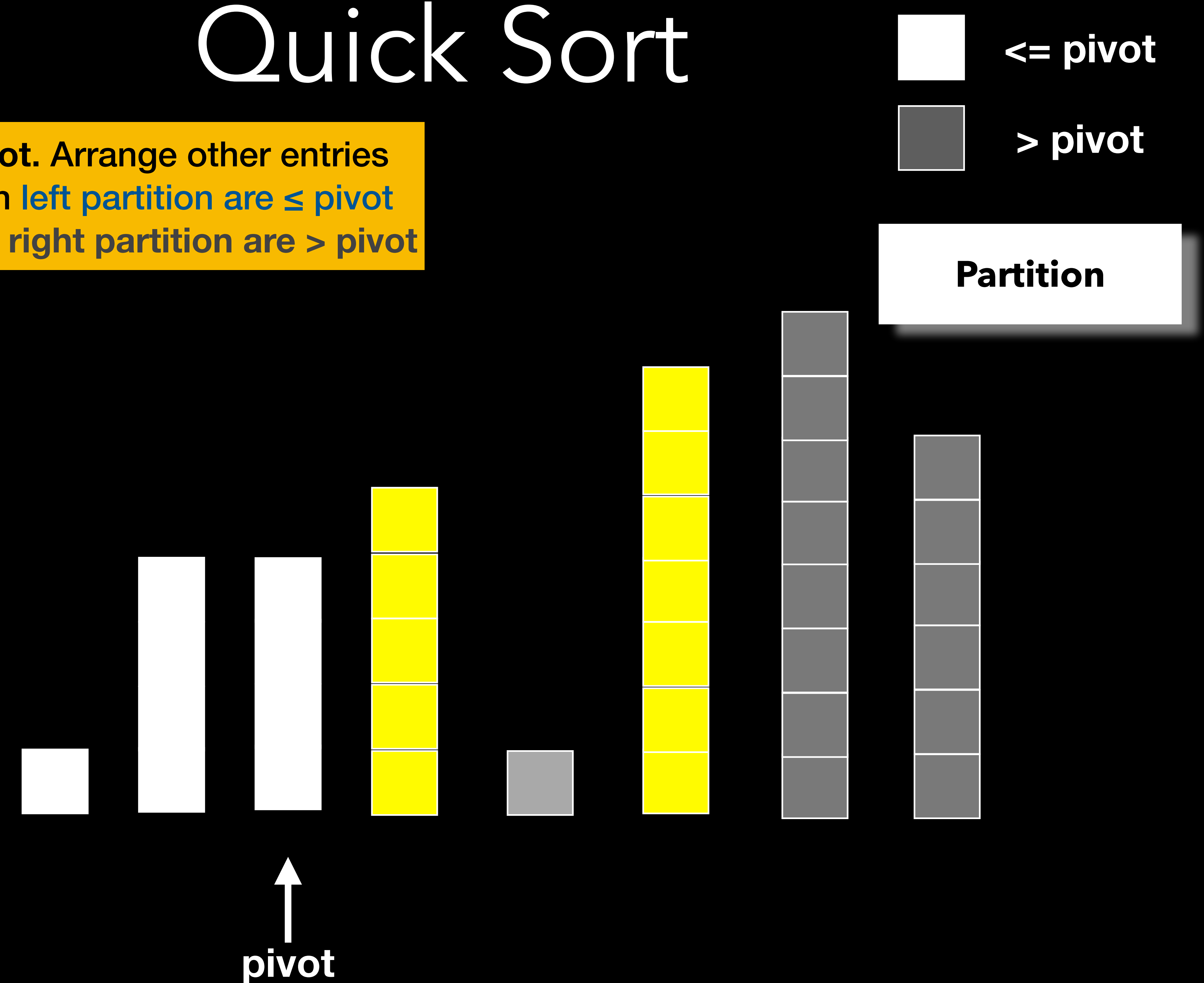

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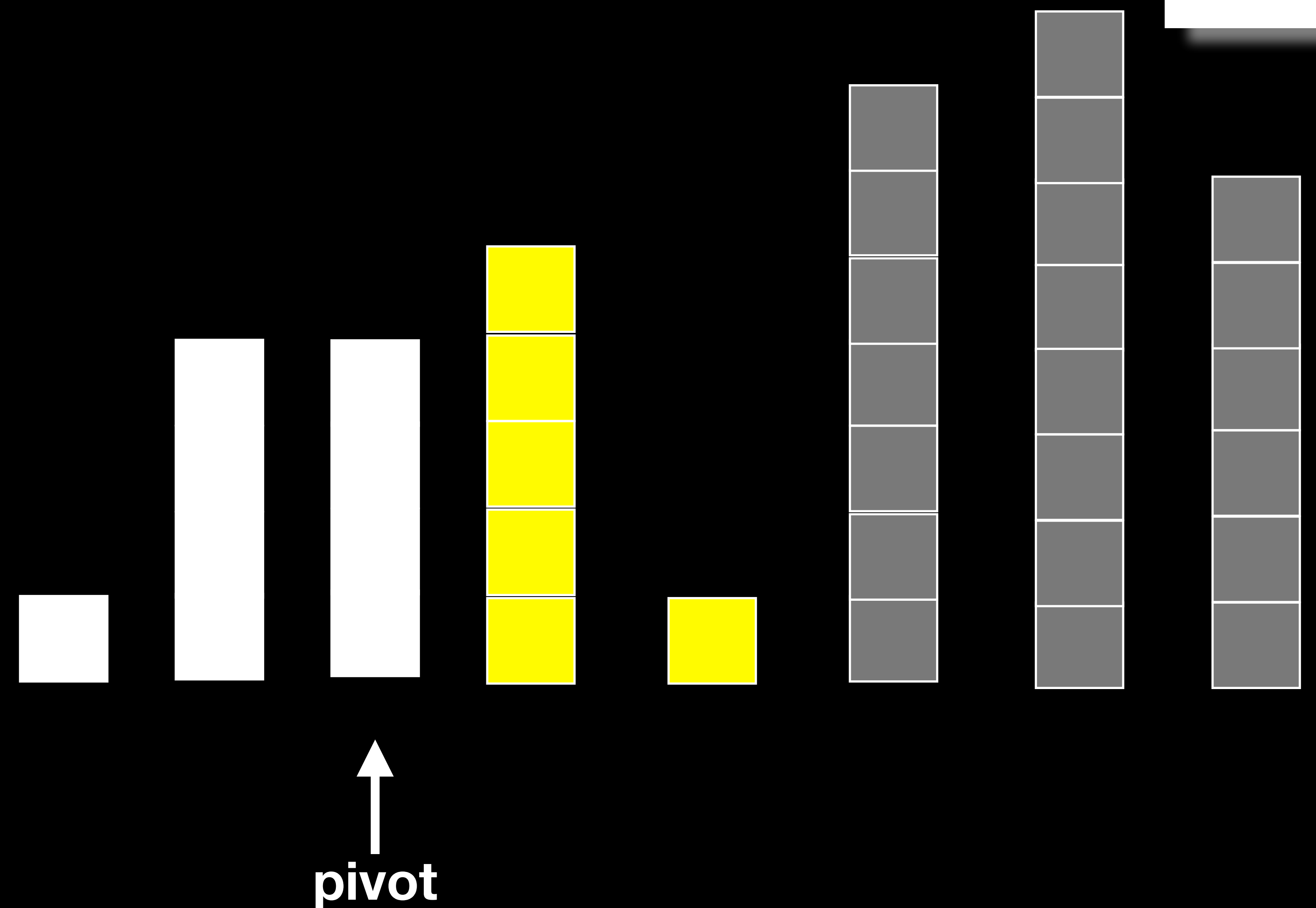

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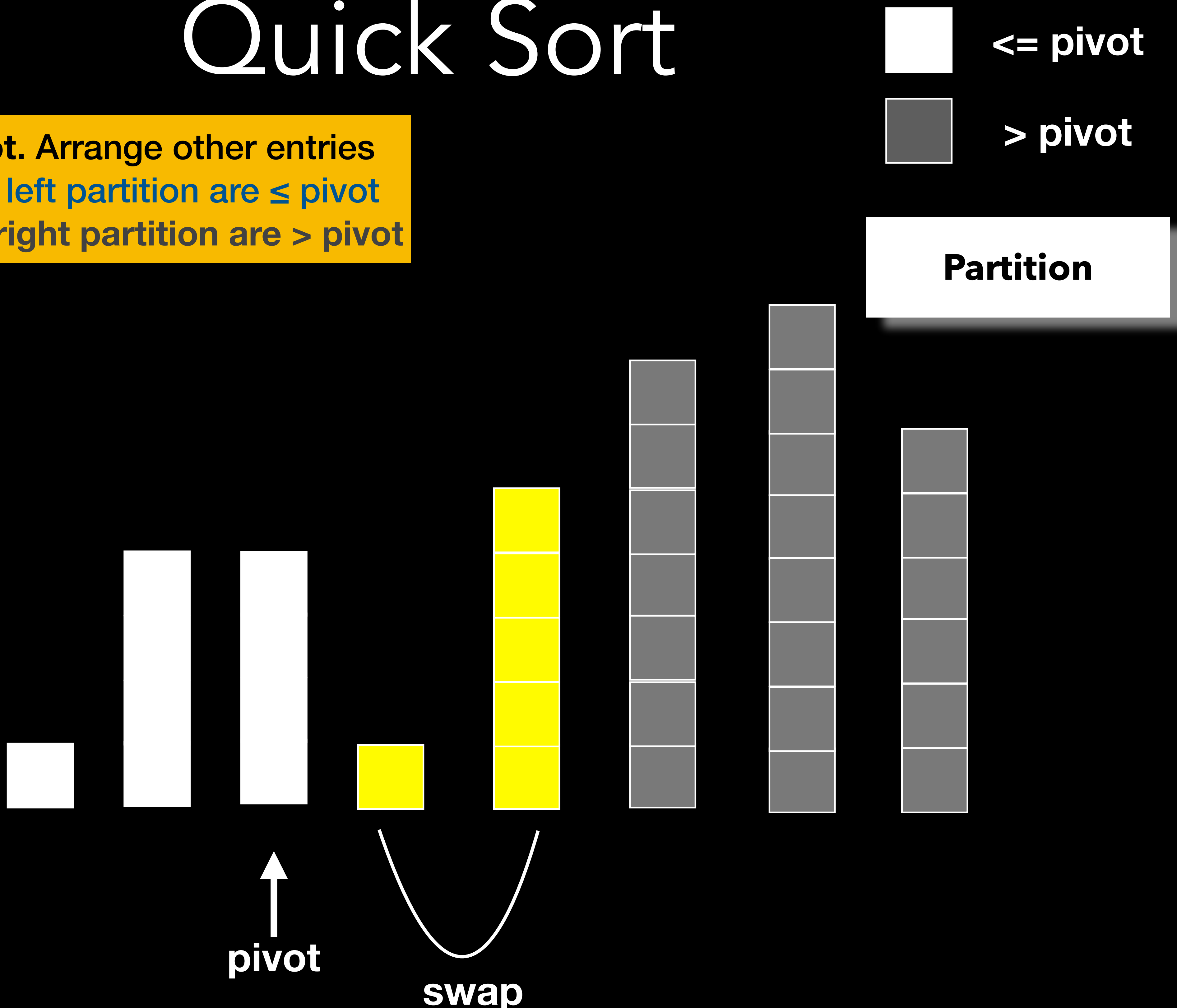

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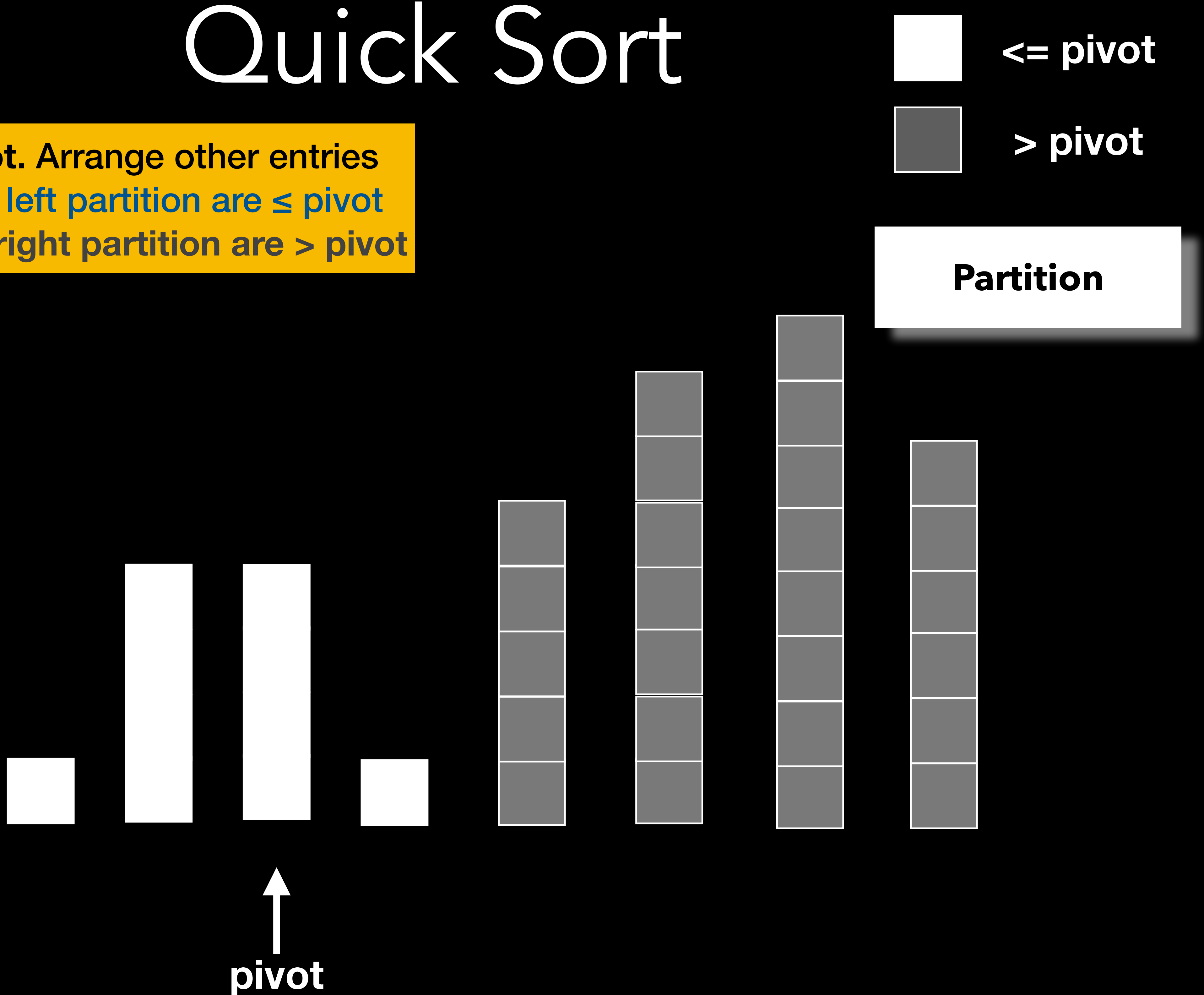

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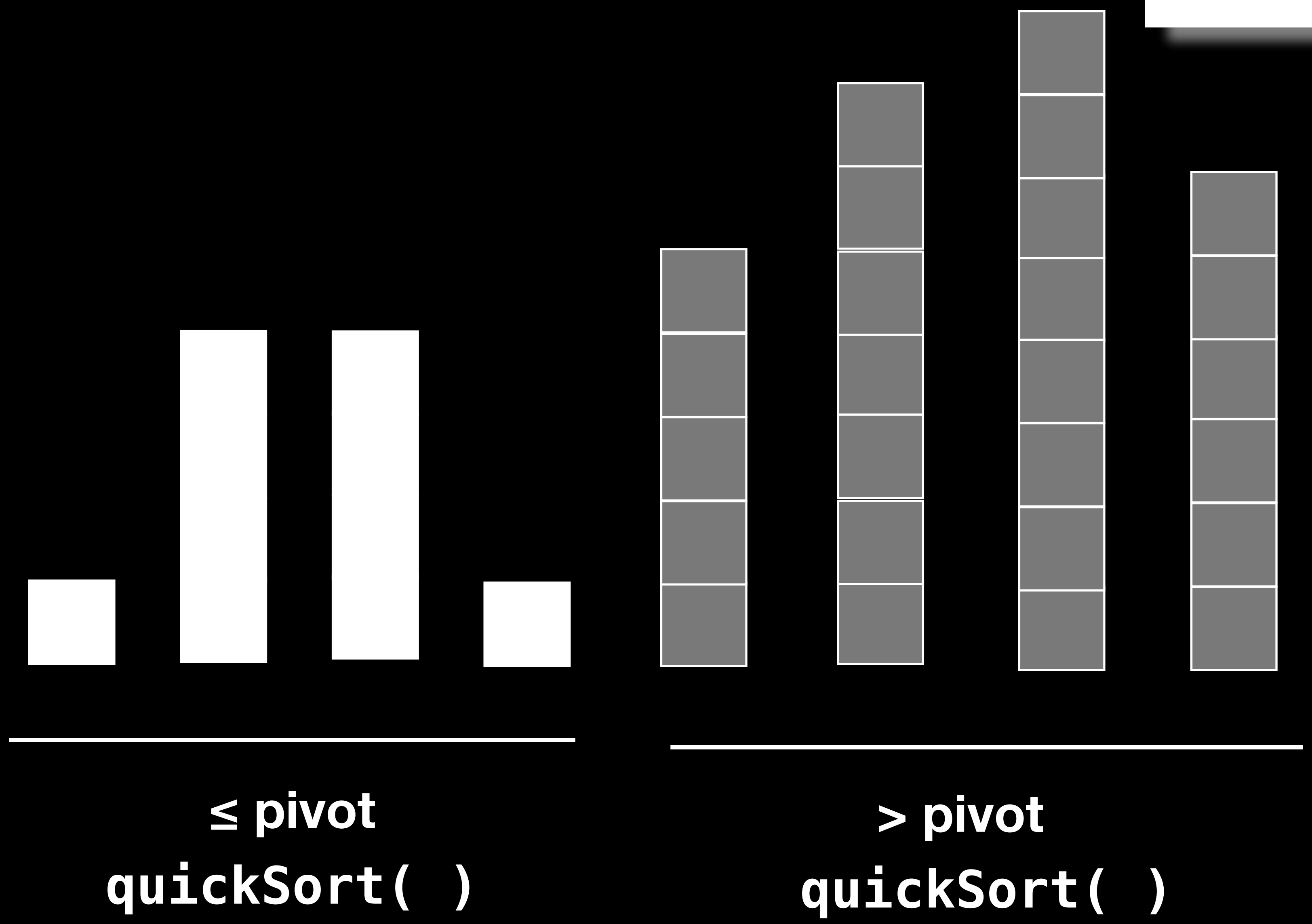
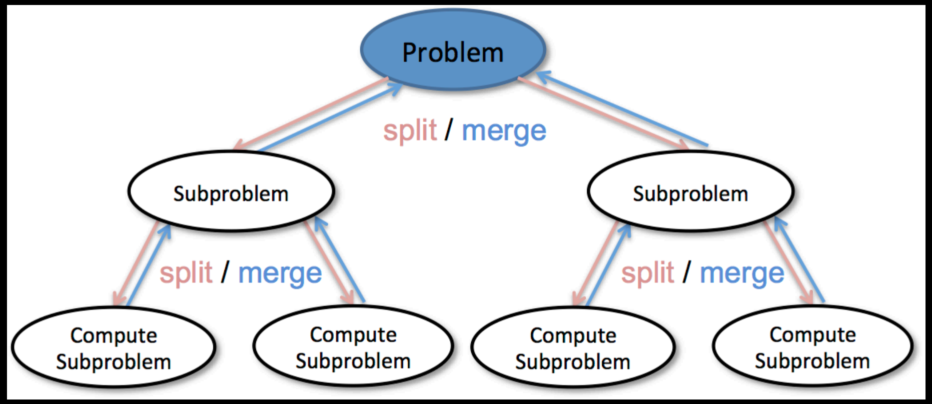


Quick Sort Analysis



Divide and Conquer

n comparisons for each partition

How many subproblems? => Depends on pivot selection

Ideally partition divides problem into two n/2 subproblems for logn recursive calls (Best case)

Possibly (though unlikely) each partition has 1 empty subarray for n recursive calls (Worst case)

```
template <class Comparable>
void quickSort(const std::vector<Comparable>& the_array,
                                         int first, int last)
{
   if (last - first + 1 < MIN_SIZE)
   {
      insertionSort(the_array, first, last);
   }
   else
   {
      // Create the partition: S1 | Pivot | S2
      int pivot_index = partition(the_array, first, last);

      // Sort subarrays S1 and S2
      quickSort(the_array, first, pivot_index);
      quickSort(the_array, pivot_index + 1, last);
   }  // end if
}  // end quickSort
```

Optimization

Optimization

How to select pivot?

How to select pivot?

Ideally median

    Need to sort array to find median

Other ideas?

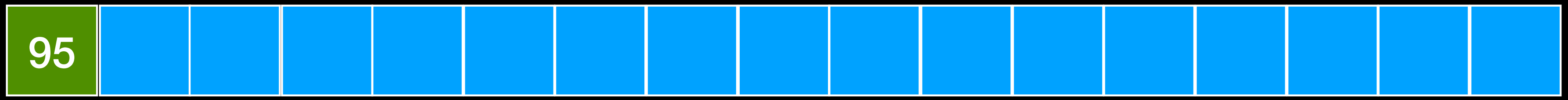
How to select pivot?

Ideally median

Need to sort array to find median

Other ideas?

Pick first



How to select pivot?

Ideally median

Need to sort array to find median

Other ideas?

Pick first, middle, last position and order them making middle the pivot

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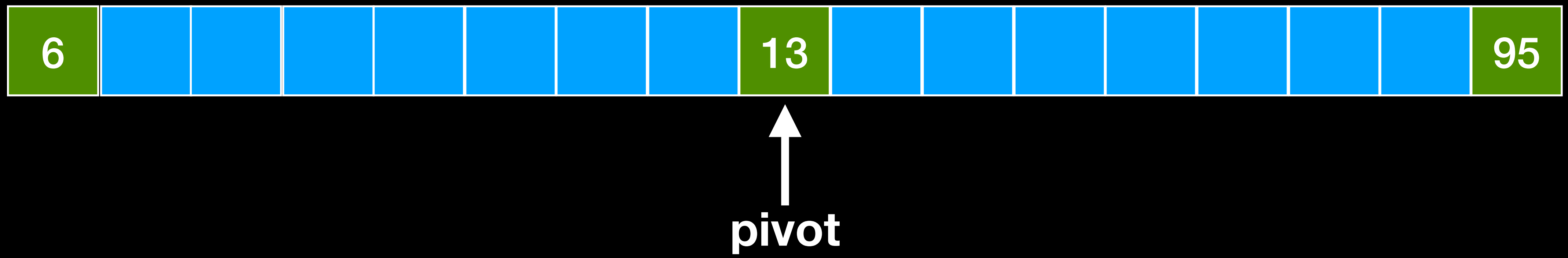


Quick Sort Analysis

Execution time DOES depend on initial arrangement of data AND on PIVOT SELECTION (luck?) => on random data can be faster than Merge Sort

Possible optimization (e.g. smart pivot selection, speed up base case, iterative instead of recursive implementation) can improve actual runtime -> fastest comparison-based sorting algorithm **on average**

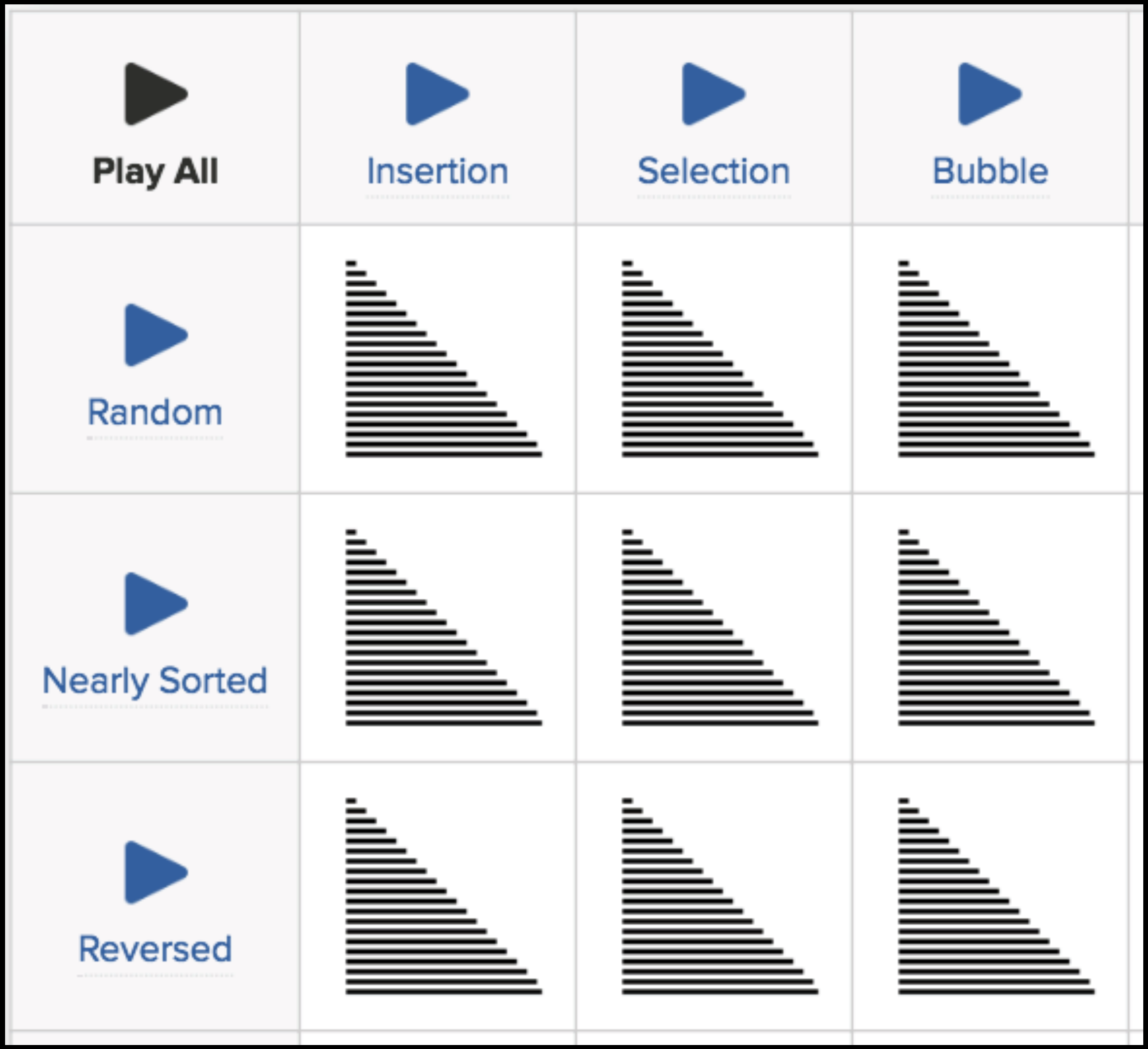
Worst Case: $O(n^2)$ comparisons and data moves

Best Case: $O(n \log n)$ comparisons and data moves

Unstable

	Worst Case	Best Case
Selection Sort	$O(n^2)$	$O(n^2)$
Insertion Sort	$O(n^2)$	$O(n)$
Bubble Sort	$O(n^2)$	$O(n)$
Merge Sort	$O(n \log n)$	$O(n \log n)$
Quick Sort	$O(n^2)$	$O(n \log n)$

https://www.toptal.com/developers/sorting-algorithms



https://www.youtube.com/watch?v=kPRA0W1kECg