Merge Sort: Shortcomings

- Merging A and B creates a new array C
  - *No obvious way to efficiently merge in place*
- Extra storage can be costly
- Inherently recursive
  - *Recursive call and return are expensive*

Alternative approach

- Extra space is required to merge
- Merging happens because elements in left half must move right and vice versa
- [2,4,6] [1,3,5]
- Can we divide so that everything to the left is smaller than everything to the right?
  - *No need to merge!*
  - *[2,1,3] [6,4,5]*

Divide and conquer without merging

- **Quick Sort (1960): Tony Hoare,** Turing Award (1980)
- Suppose the median {0, 0, 0, 1, 1, 2, 10, 10} value in A is m
- Move all values ≤ m to left half of A
  - *Right half has values > m*
  - *This shifting can be done in place, in time O(n)*
- Recursively sort left and right halves
- A is now sorted! No need to merge
  - *O(n log n) : Time Complexity wise same, no extra array for merge*

Divide and conquer without merging

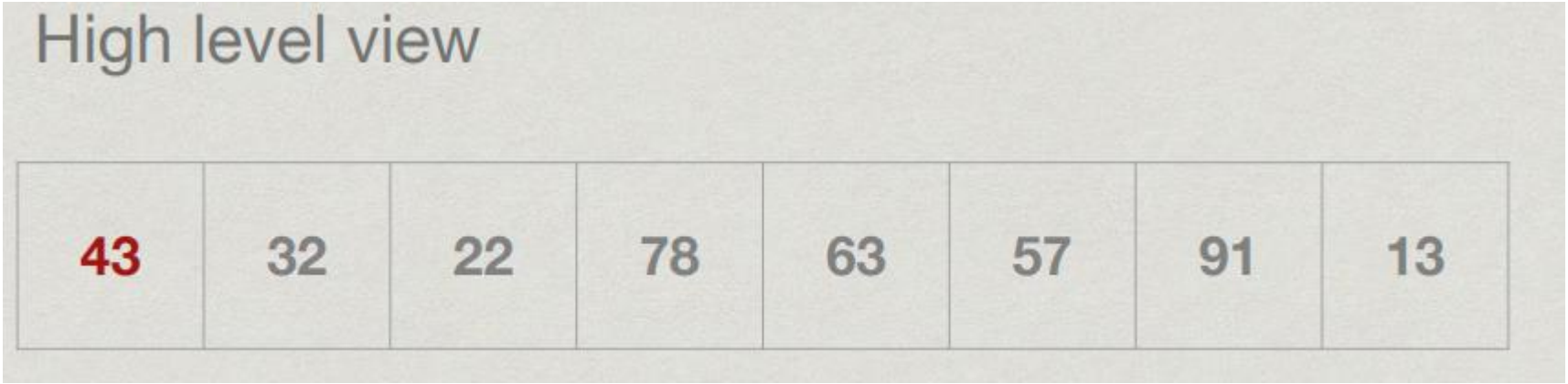
- How do we find the median?
- Sort and pick up middle element
- But our aim is to sort! (Chicken Egg Problem)

- Instead, pick up some value in A — **pivot**
- Split A with respect to this pivot element

Quick Sort

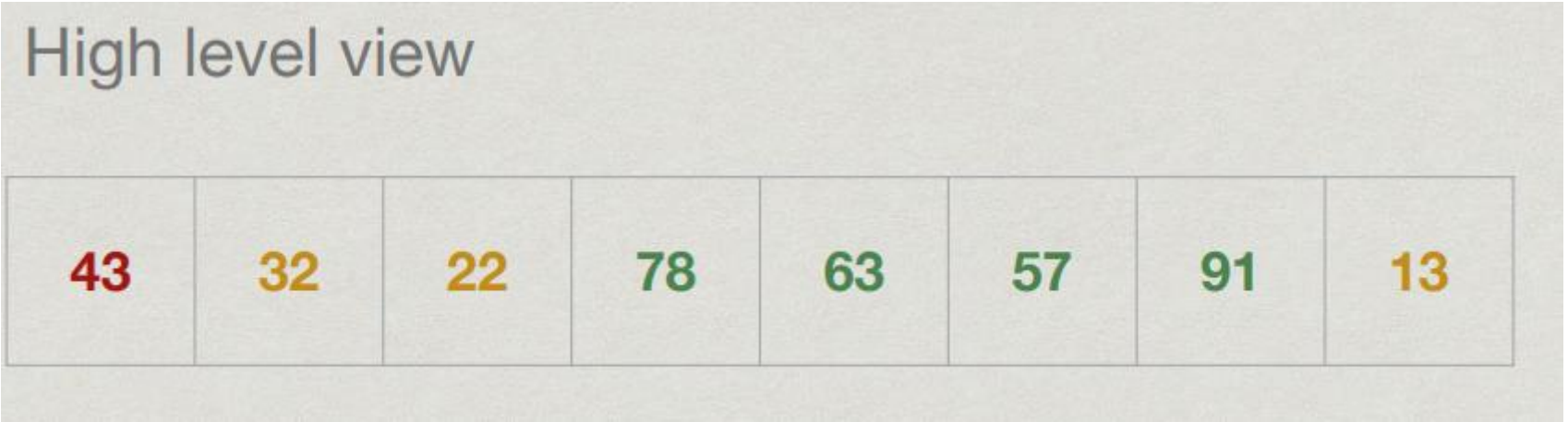
- Choose a pivot element
  - *Typically the first value in the array*
- Partition A into lower and upper parts with respect to pivot
- Move pivot between lower and upper partition
- Recursively sort the two partitions

Quicksort



Quicksort

High level view



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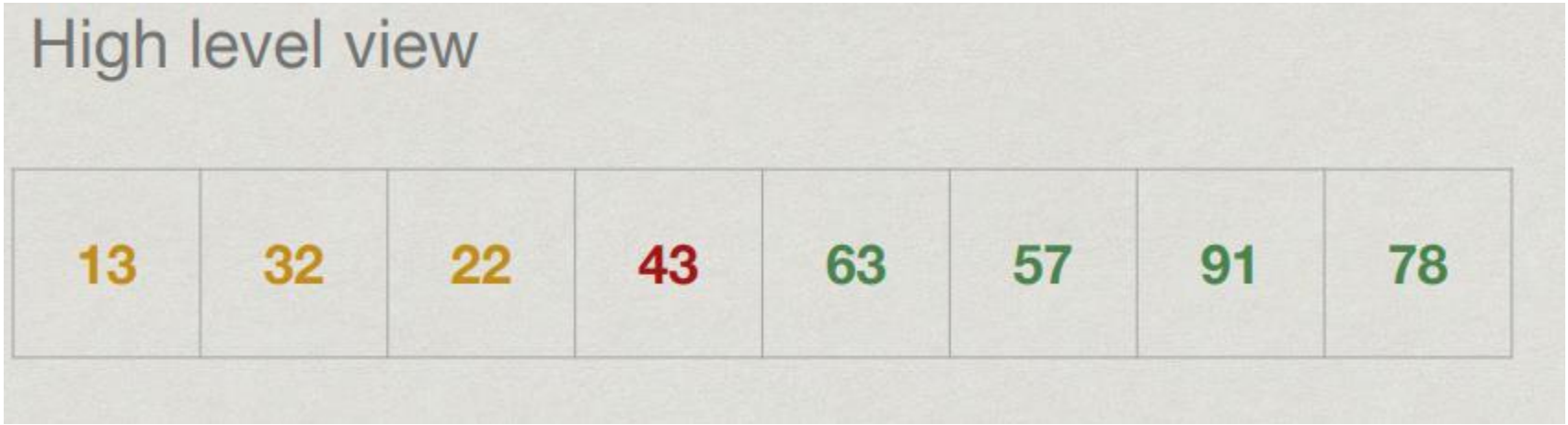

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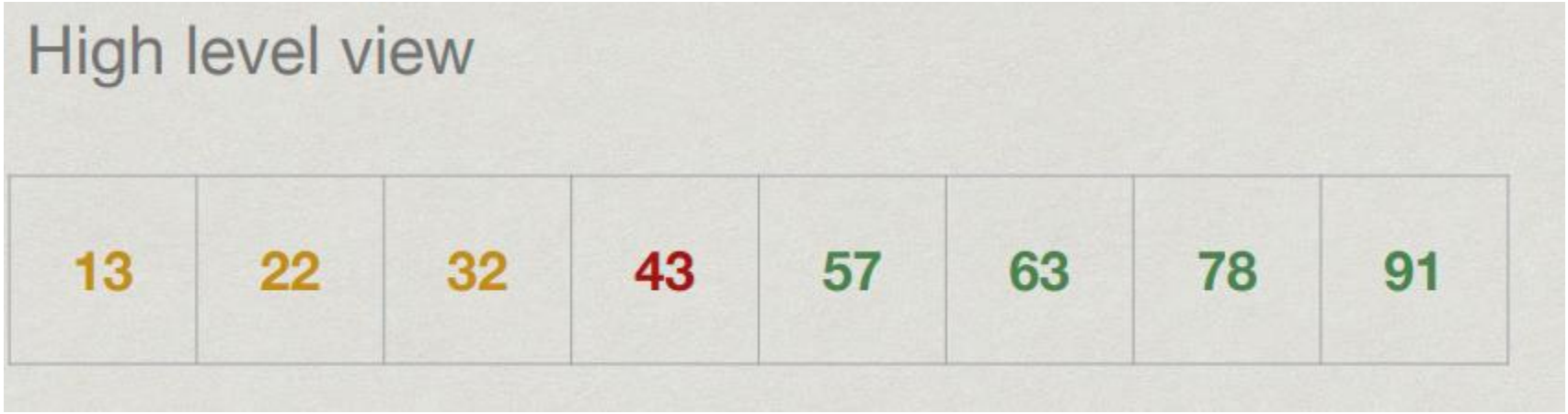


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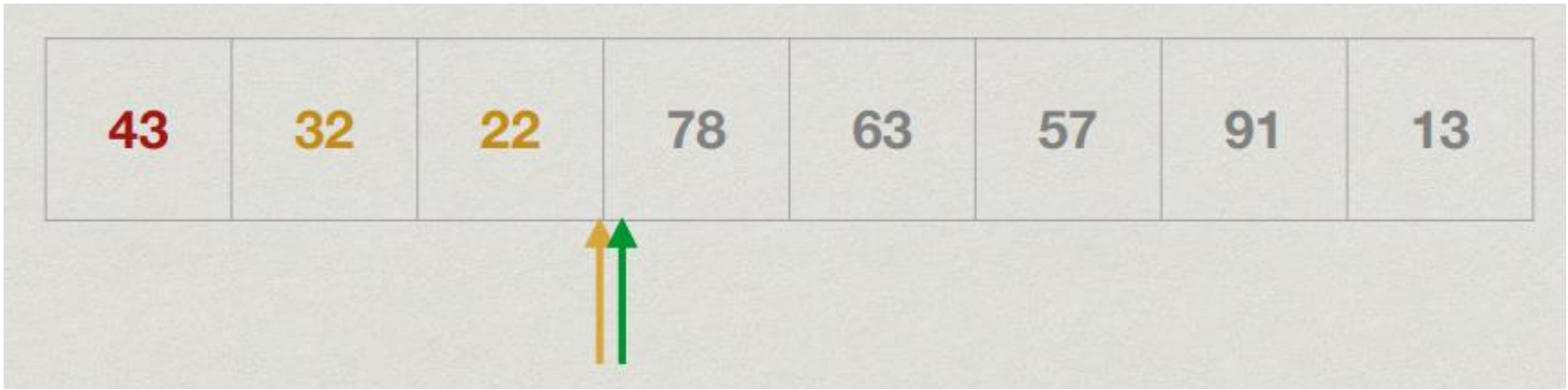
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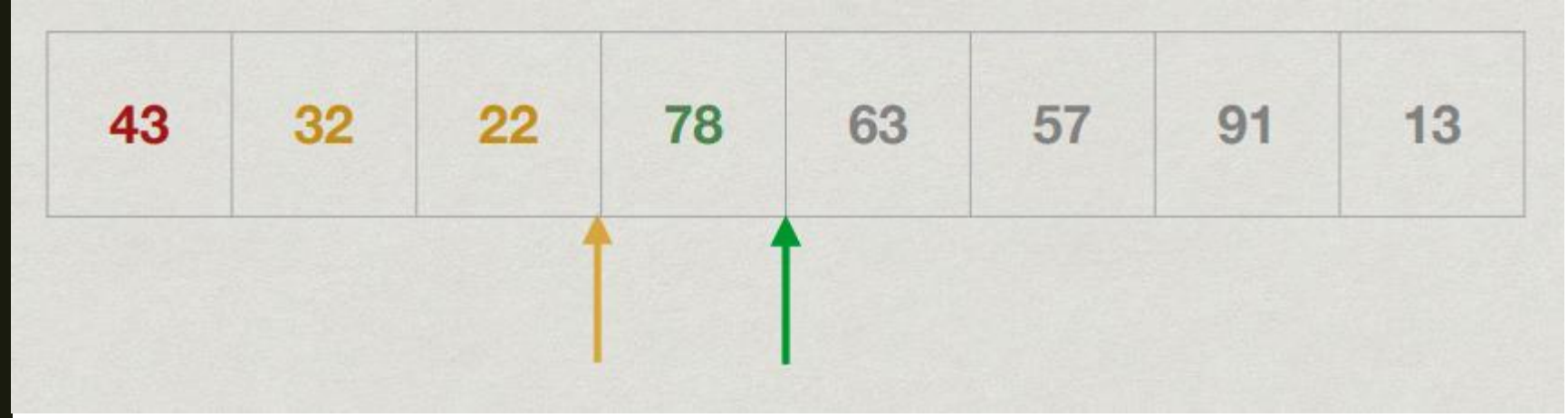
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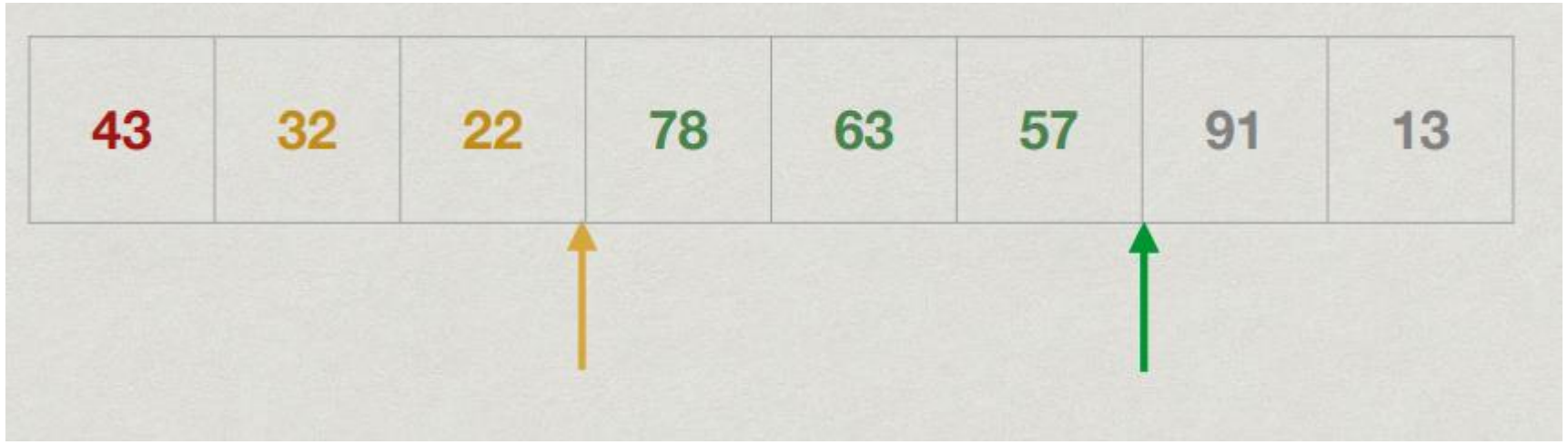
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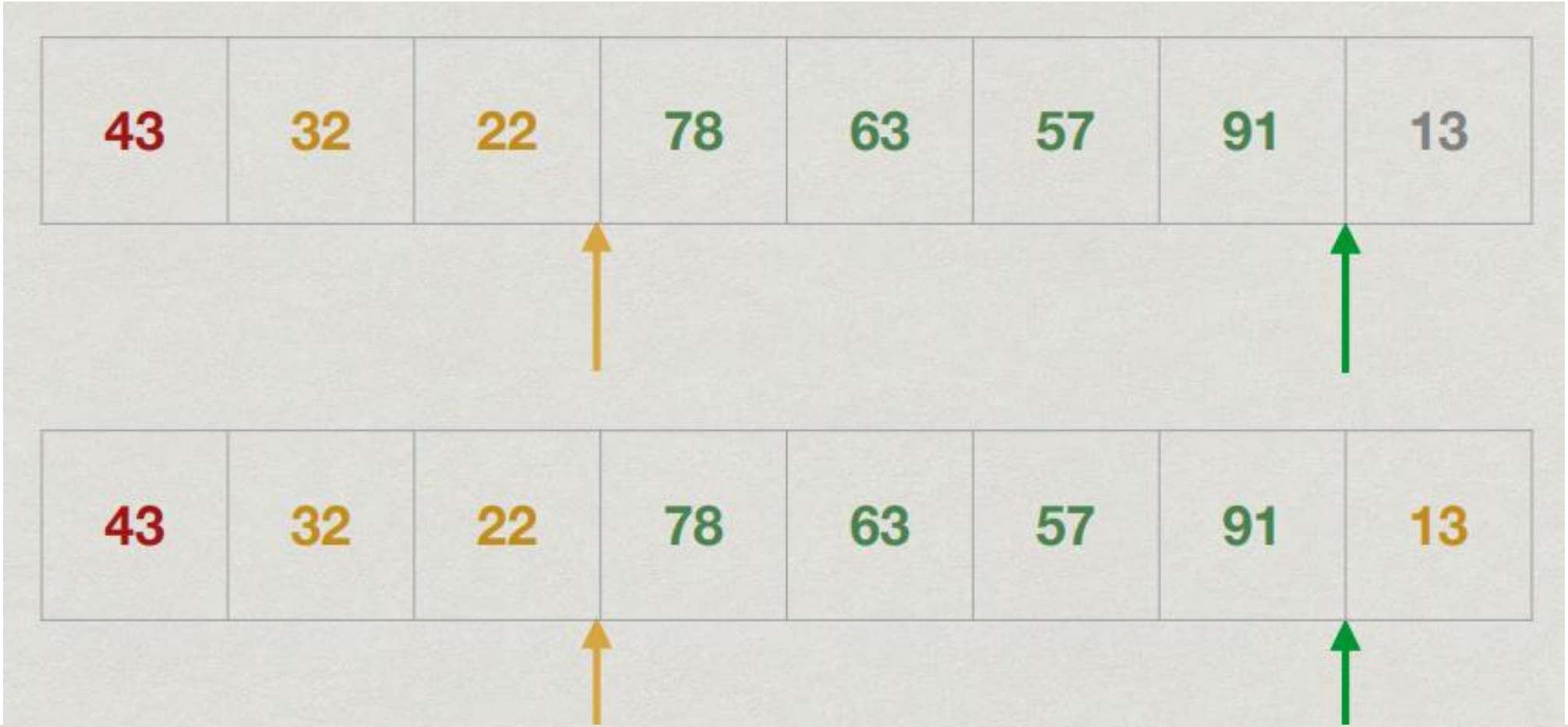
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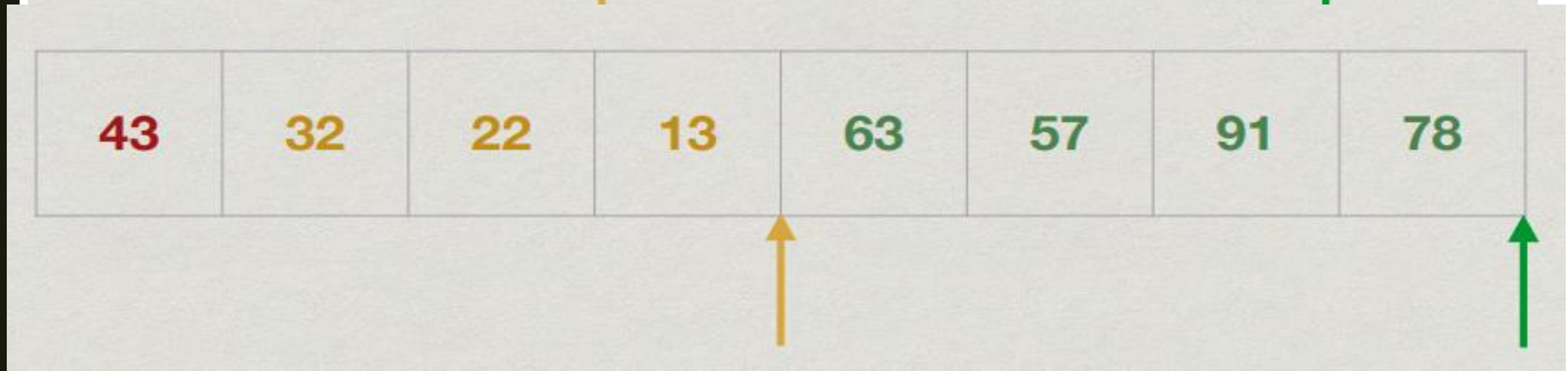
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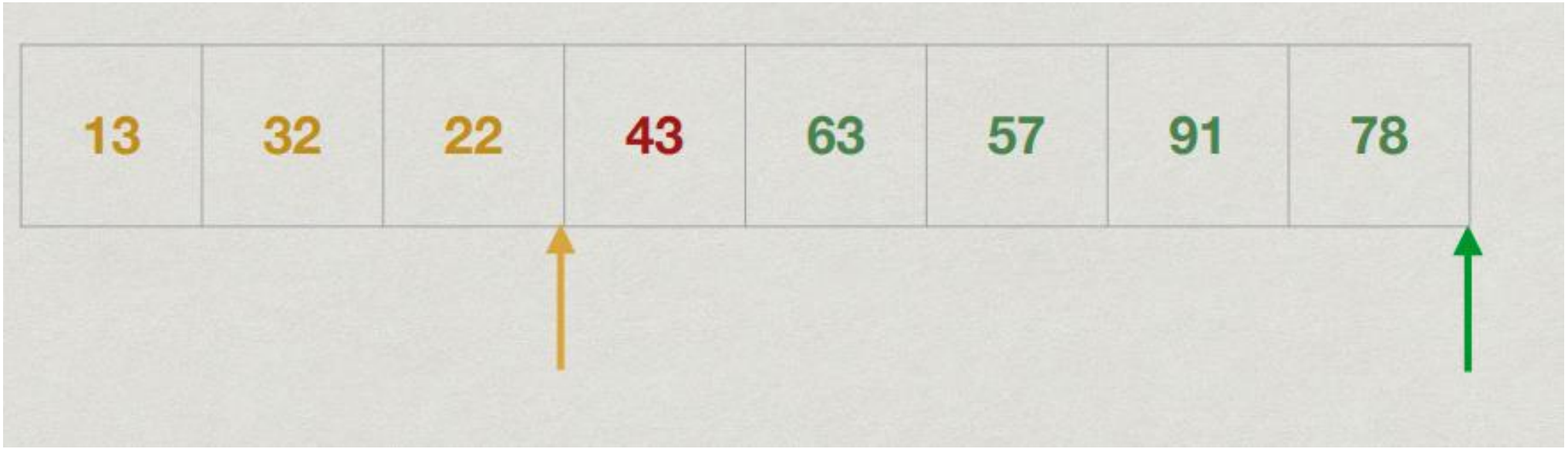
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Quicksort: Implementation

```
Quicksort(A,l,r) // Sort A[l..r-1]
if (r - l <= 1)) return; // Base case
// Partition with respect to pivot, a[l]
yellow = l+1;
for (green = l+1; green < r; green++)
if (A[green] <= A[l])
swap(A,yellow,green);
yellow++;
swap(A,l,yellow-1); // Move pivot into place
Quicksort(A,l,yellow); // Recursive calls
Quicksort(A,yellow+1,r);
```

Analysis of Quicksort

- Worst case
  - *Pivot is maximum or minimum*
  - *One partition is empty*
  - *Other is size n-1*
- Already sorted array is worst case input O(n2)