MONASH
INFORMATION
TECHNOLOGY

FIT2004
Algorithms and Data Structures

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Referencing materials by
Nathan Companez, Aamir Cheema, Arun Konagurthu and Lloyd Allison

Faculty of Information Technology, Monash University

Ready?

Agenda

- Quick Sort

Agenda

- Quick Sort
  - Analysis of time
  - Analysis of space

Agenda

- Quick Sort
  - Analysis of time
  - Analysis of space
  - But in detail!

Agenda

- Quick Sort
  - Analysis of time
  - Analysis of space
  - But in detail!
    - Partitioning strategy etc…

Let us begin…

Quicksort
Brief description

- How would you describe quick sort?

Quicksort
Brief description

- How would you describe quick sort?
  - Divide and conquer

Quicksort
Brief description

- How would you describe quick sort?
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pivot

Quicksort
Brief description

- How would you describe quick sort?
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Quicksort
Brief description

- How would you describe quick sort?
  - Divide and conquer

- Partition-based on the pivot
  - Smaller to the left of pivot
  - Bigger to the right of pivot

Quicksort
Brief description

- How would you describe quick sort?
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  - Smaller or equal to the left of pivot
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Quicksort
Brief description

- How would you describe quick sort?
  - Divide and conquer
- Partition-based on the pivot
  - Smaller or equal to the left of pivot
  - Bigger to the right of pivot
- Divide based on the partition

Quicksort
Brief description

- How would you describe quick sort?
  - Divide and conquer
- Partition-based on the pivot
  - Smaller or equal to the left of pivot
  - Bigger to the right of pivot
- Divide based on the partition

Repeat

- How would you describe quick sort?
  - Divide and conquer
- Partition-based on the pivot
  - Smaller or equal to the left of pivot
  - Bigger to the right of pivot
- Divide based on the partition

Repeat
Till partition size 1…

Quicksort
Brief description

- How would you describe quick sort?
  - Divide and conquer

- Partition-based on the pivot
  - Smaller or equal to the left of pivot
  - Bigger to the right of pivot

- Divide based on the partition

Repeat
Till partition size 1…

Quicksort
Brief description

- How would you describe quick sort?
  - Divide and conquer
- Partition-based on the pivot
  - Smaller or equal to the left of pivot
  - Bigger to the right of pivot
- Divide based on the partition

Repeat
Till partition size 1…

Questions?

Quicksort
Example

- Given a list

2	8	7	1	3	4	5	6

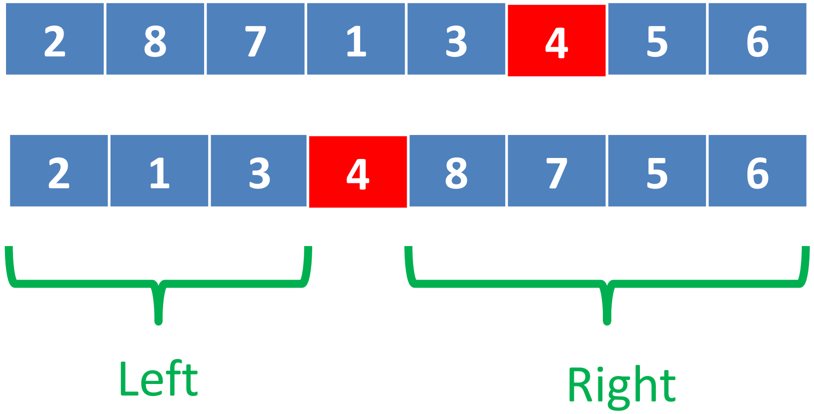
Quicksort
Example

- Given a list
- Choose a pivot (doesn't matter which)

2	8	7	1	3	4	5	6

Quicksort
Example

- Given a list
- Choose a pivot (doesn't matter which)
- Ensure invariant
  - Left <= pivot
  - Right > pivot



Quicksort
Example

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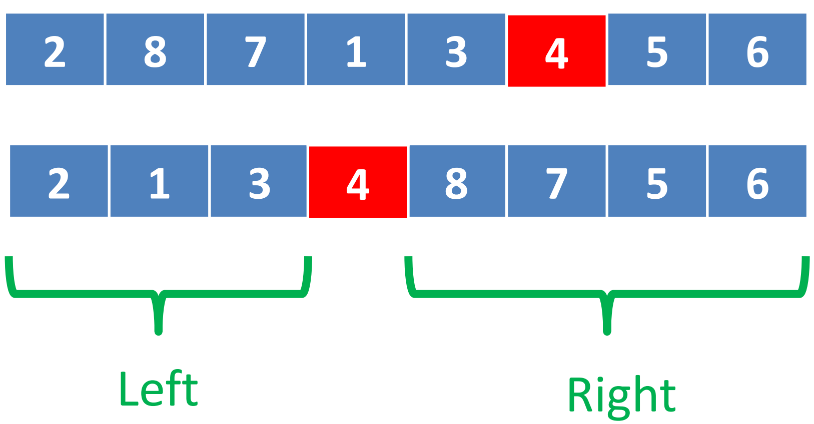
- Given a list
- Choose a pivot (doesn't matter which)
- Ensure invariant
  - Left <= pivot
  - Right > pivot

Partitioning



Quicksort
Example

- Given a list
- Choose a pivot (doesn't matter which)
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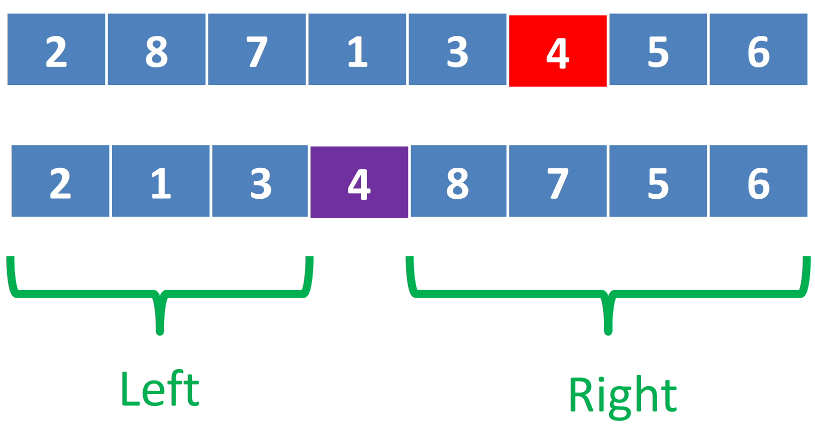
  - Left <= pivot
  - Right > pivot

Partitioning

- Pivot is now in sorted position (or in order)

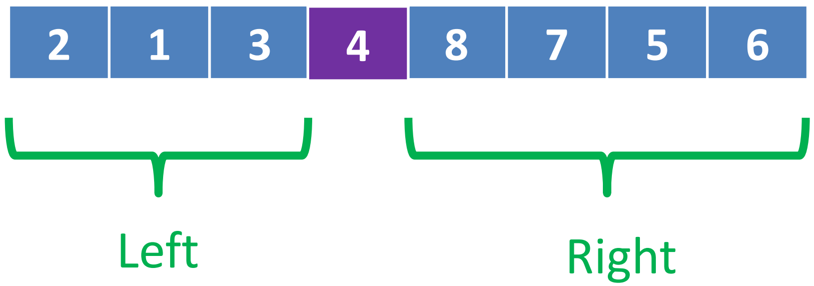


Quicksort
Example

- Given a list
- Choose a pivot (doesn't matter which)
- Ensure invariant
  - Left <= pivot
  - Right > pivot

Partitioning

- Pivot is now in sorted position (or in order)
- Then we repeat for left and right



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Partitioning

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2	1	3	4	8	7	5	6

Quicksort

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1	2	3	4	8	7	5	6

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1	2	3	4	8	7	5	6

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Partitioning

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1	2	3	4	8	7	5	6

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  – Left <= pivot
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Partitioning

- Pivot is now in sorted position (or in order)
- Then we repeat for left and right

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Quicksort

Example

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Partitioning

1	2	3	4	8	7	5	6

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- Given a list
- Choose a pivot (doesn't matter which)
- Ensure invariant
  - Left <= pivot
  - Right > pivot

Partitioning

- Pivot is now in sorted position (or in order)
- Then we repeat for left and right
- Till sorted

1	2	3	4	5	6	7	8

Questions?

- What is partitioning?

- What is partitioning?
  - Separate the list into parts

Quicksort
Partitioning

- What is partitioning?
  - Separate the list into parts
  - Here, mainly the left and the right

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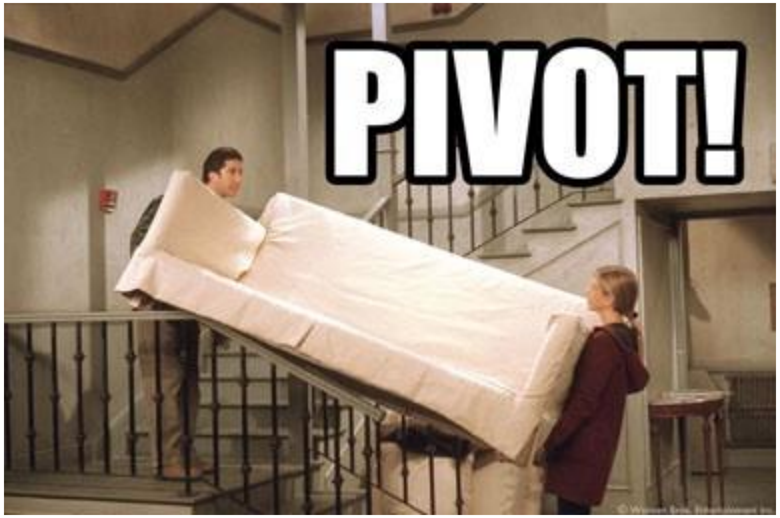
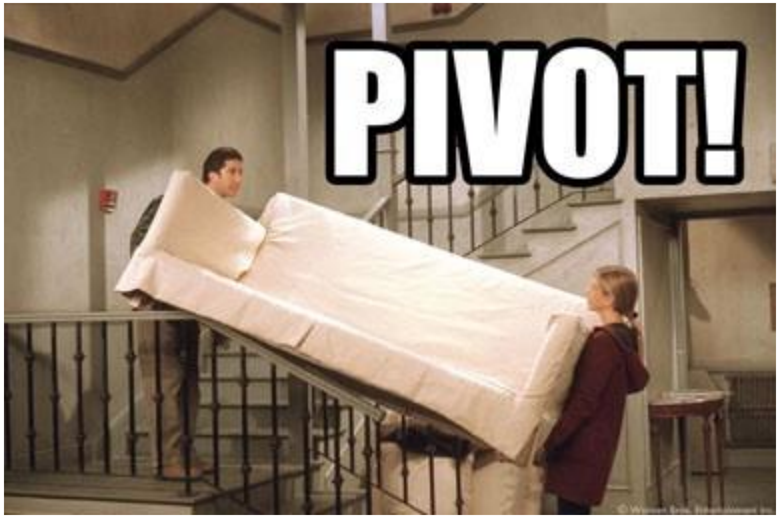
- Partition is based-on pivot



Quicksort
Partitioning

- What is partitioning?
  - Separate the list into parts
  - Here, mainly the left and the right

- Partition is based-on pivot
  - Out-of-place
  - Hoare's
  - Lomuto's



Questions?

- Not in-place

- Not in-place

2	8	7	1	3	4	5	6

LEFT

RIGHT

Quicksort
Out-of-place Partitioning

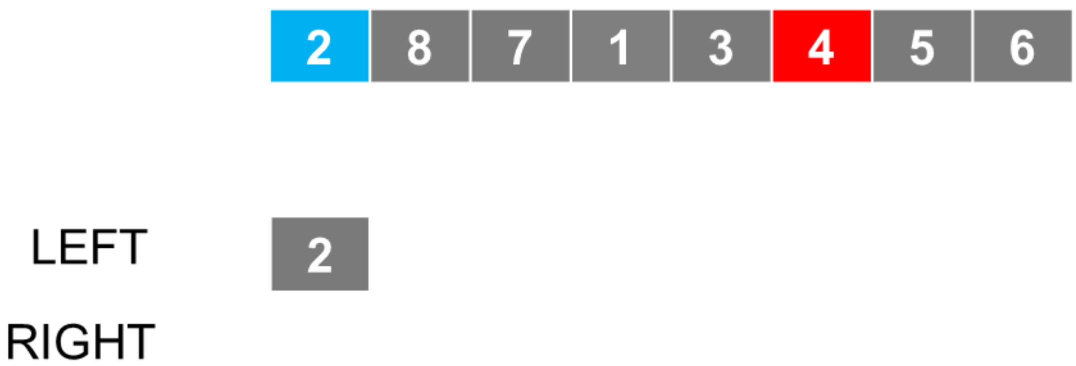
- Not in-place

2	8	7	1	3	4	5	6

LEFT

RIGHT

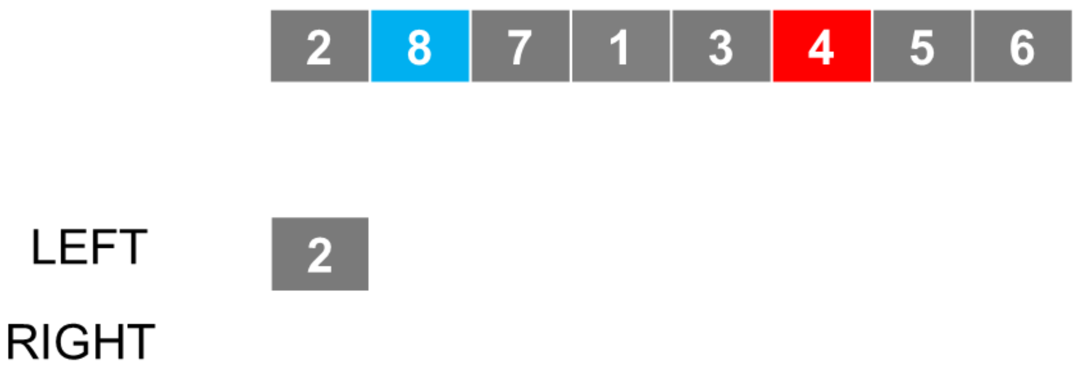
- Not in-place



Quicksort

Out-of-place Partitioning

- Not in-place



Quicksort
Out-of-place Partitioning

- Not in-place

2	8	7	1	3	4	5	6

LEFT	2
RIGHT	8

Quicksort
Out-of-place Partitioning

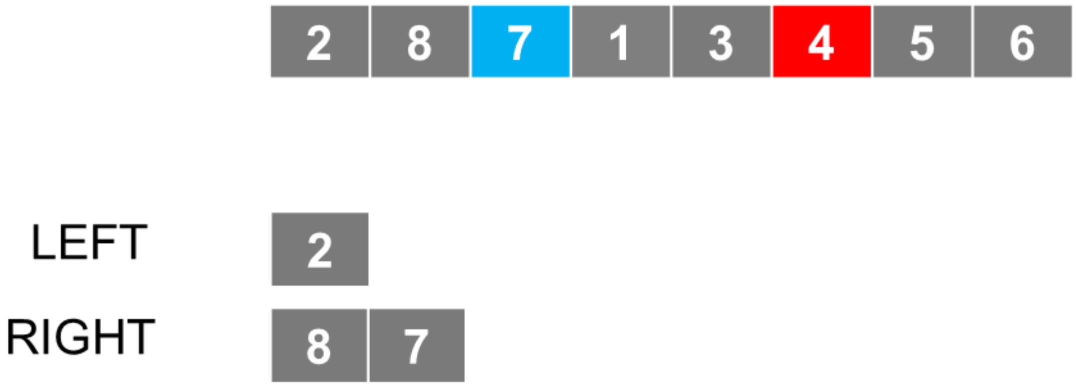
- Not in-place

2	8	7	1	3	4	5	6

LEFT	2
RIGHT	8

Quicksort
Out-of-place Partitioning

- Not in-place



Quicksort
Out-of-place Partitioning

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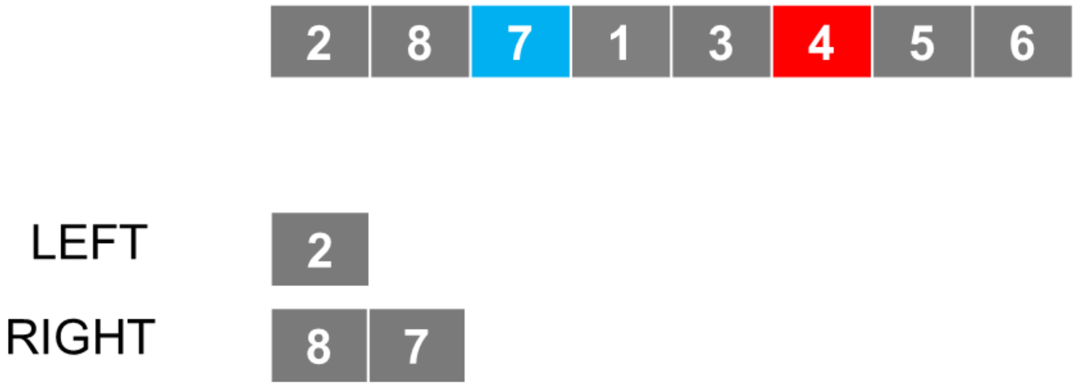
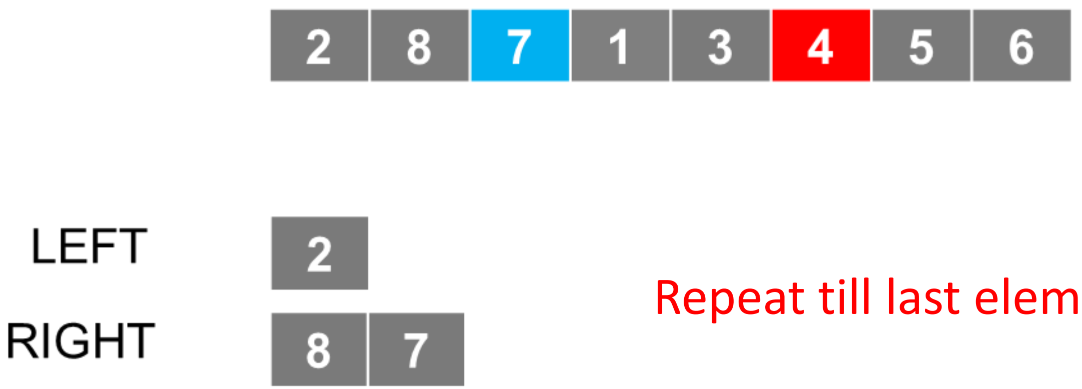


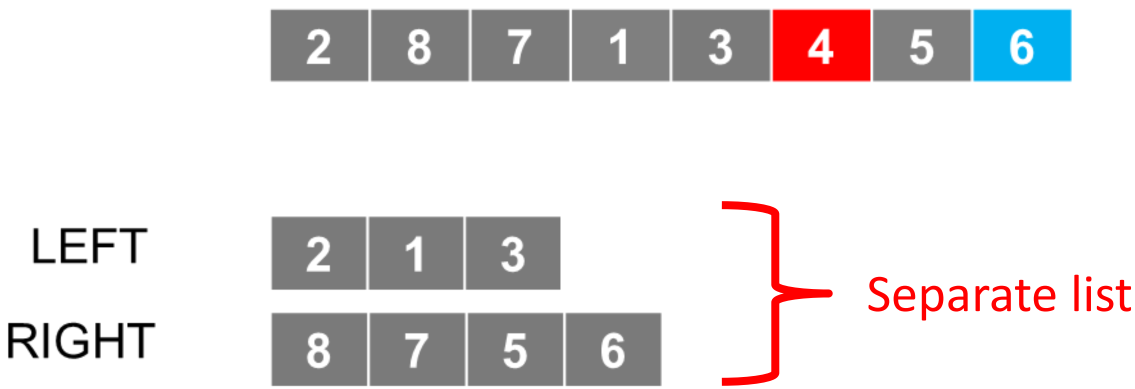
- Not in-place



Repeat till last element

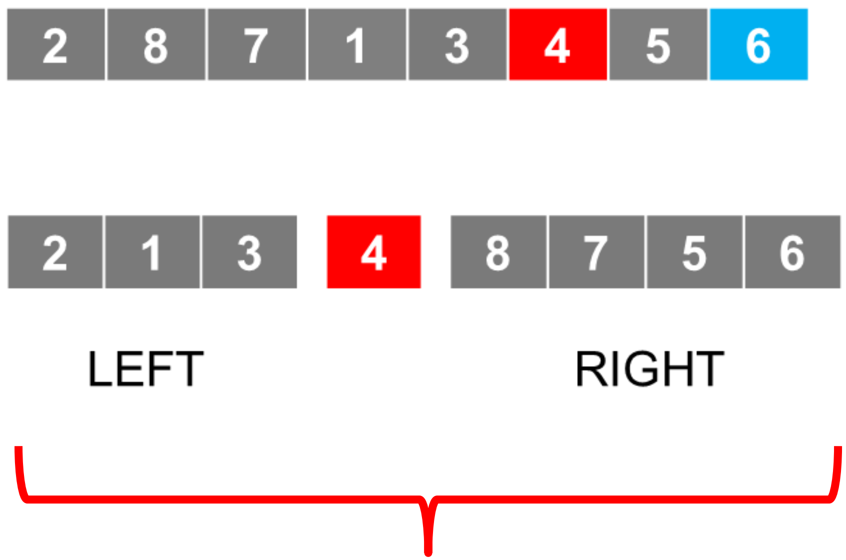
Out-of-place Partitioning

- Not in-place



Quicksort
Out-of-place Partitioning

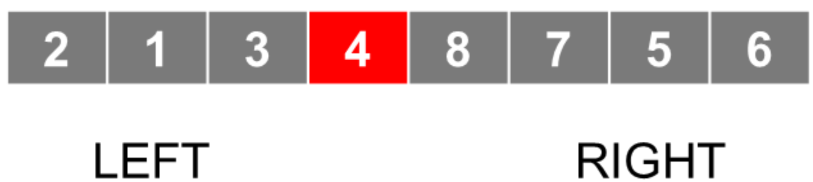
- Not in-place



Separate list/ onto original list

Quicksort
Out-of-place Partitioning

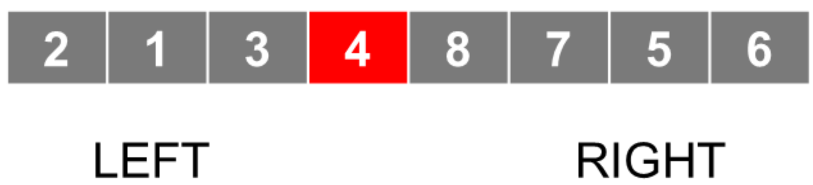
- Not in-place



Quicksort

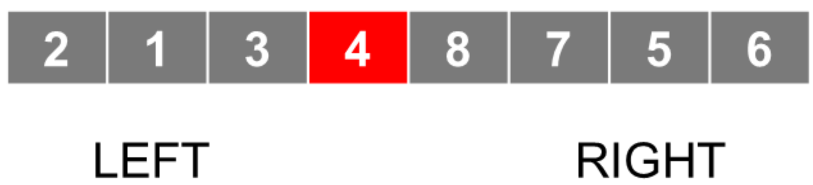
Out-of-place Partitioning

- Not in-place
  - Need left temporary list
  - Need right temporary list



Quicksort
Out-of-place Partitioning

- Not in-place
  - Need left temporary list
  - Need right temporary list
  - Combined back to the original list



Quicksort
Out-of-place Partitioning

- Not in-place
  - Need left temporary list
  - Need right temporary list
  - Combined back to the original list

2	1	3	4	8	7	5	6

LEFT RIGHT

  - Is the algorithm stable?

Quicksort
Out-of-place Partitioning

- Not in-place
  - Need left temporary list
  - Need right temporary list
  - Combined back to the original list

2	1	3	4	8	7	5	6

LEFT RIGHT

  - Is the algorithm stable?
    - <= pivot to the left
    - > pivot to the right

Quicksort
Out-of-place Partitioning

- Not in-place
  - Need left temporary list
  - Need right temporary list
  - Combined back to the original list

2	1	3	4	8	7	5	6

LEFT RIGHT

  - Is the algorithm stable?
    - <= pivot to the left: everything == pivot to the left of the pivot!
    - > pivot to the right

Quicksort
Out-of-place Partitioning

- Not in-place
  - Need left temporary list
  - Need right temporary list
  - Combined back to the original list

2	1	3	4	8	7	5	6

LEFT RIGHT

  - Is the algorithm stable? NO
    - <= pivot to the left: everything == pivot to the left of the pivot!
    - > pivot to the right

Quicksort
Out-of-place Partitioning

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- Not in-place
  - Need left temporary list
  - Need right temporary list
  - Combined back to the original list

2	1	3	4	8	7	5	6

LEFT RIGHT

  - Is the algorithm stable? NO
    - <= pivot to the left: everything == pivot to the left of the pivot!
    - > pivot to the right
    - But we can make it stable by having 2 separate list for == pivot
      - Anything can be stable with more memory!

Quicksort
Out-of-place Partitioning

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- Not in-place
  - Need left temporary list
  - Need right temporary list
  - Combined back to the original list

O(N) additional space beside recursive stack

2	1	3	4	8	7	5	6

LEFT RIGHT

  - Is the algorithm stable? NO
    - <= pivot to the left: everything == pivot to the left of the pivot!
    - > pivot to the right
    - But we can make it stable by having 2 separate list for == pivot
      - Anything can be stable with more memory!

Questions?

In-place Partitioning (Hoare’s)

- We want to make it in-place
- We want to make it fast
- We want to make it stable

Quicksort

In-place Partitioning (Hoare's)

- We want to make it in-place
  - Save memory
- We want to make it fast
- We want to make it stable

Quicksort
In-place Partitioning (Hoare's)

- We want to make it in-place
  - Save memory
- We want to make it fast
  - Avoid copying many items
- We want to make it stable

Quicksort

In-place Partitioning (Hoare's)

- We want to make it in-place
  - Save memory
- We want to make it fast
  - Avoid copying many items
  - Avoid swapping many times
- We want to make it stable

- We want to make it in-place
  - Save memory
- We want to make it fast
  - Avoid copying many items
  - Avoid swapping many times
- We want to make it stable
  - Can we?

Quicksort

In-place Partitioning (Hoare's)

- We want to make it in-place
  - Save memory
- We want to make it fast
  - Avoid copying many items
  - Avoid swapping many times
    - Main focus here: Swap every item only once except pivot
- We want to make it stable
  - Can we?

Quicksort
In-place Partitioning (Hoare's)

- We want to make it in-place
  - Save memory
- We want to make it fast
  - Avoid copying many items
  - Avoid swapping many times
    - Main focus here: Swap every item only once except pivot
- We want to make it stable
  - Can we?

- I will use Nathan's slide here for consistency
  - But I will add in notes on top

Partitioning: In place (Hoare's)

Swap pivot to the front (position 1)

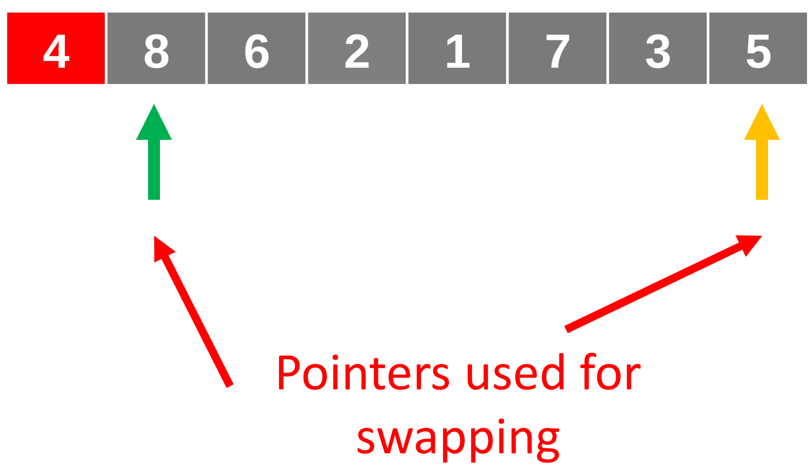
Index starts from 1

2	8	6	4	1	7	3	5

Partitioning: In place (Hoare's)

Swap pivot to the front (position 1)

L_bad = 2, R_bad = N



Partitioning: In place (Hoare's)

Swap pivot to the front (position 1)

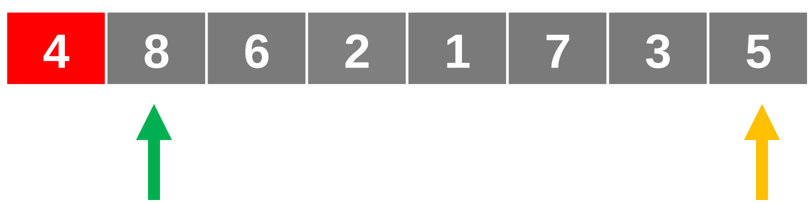
L_bad = 2, R_bad = N

Repeat until L_bad and R_bad cross

 move L_bad right until we find a "bad" element, i.e. > pivot

 move R_bad left until we find a "bad" element, i.e. < pivot

 swap these elements



Partitioning: In place (Hoare's)

Swap pivot to the front (position 1)

L_bad = 2, R_bad = N

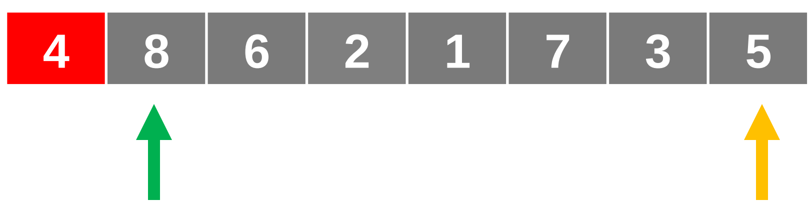
Repeat until L_bad and R_bad cross

Terminating condition

    move L_bad right until we find a "bad" element, i.e. > pivot

    move R_bad left until we find a "bad" element, i.e. < pivot

    swap these elements



Partitioning: In place (Hoare's)

Swap pivot to the front (position 1)

L_bad = 2, R_bad = N

Repeat until L_bad and R_bad cross

- move L_bad right until we find a "bad" element, i.e. > pivot
- move R_bad left until we find a "bad" element, i.e. < pivot
- swap these elements

Recall
left <= pivot
right > pivot

4	8	6	2	1	7	3	5

Partitioning: In place (Hoare's)

Swap pivot to the front (position 1)

L_bad = 2, R_bad = N

Repeat until L_bad and R_bad cross

- move L_bad right until we find a "bad" element, i.e. > pivot
- move R_bad left until we find a "bad" element, i.e. < pivot
- swap these elements

Swap once
only per element

4	8	6	2	1	7	3	5

Partitioning: In place (Hoare's)

Swap pivot to the front (position 1)

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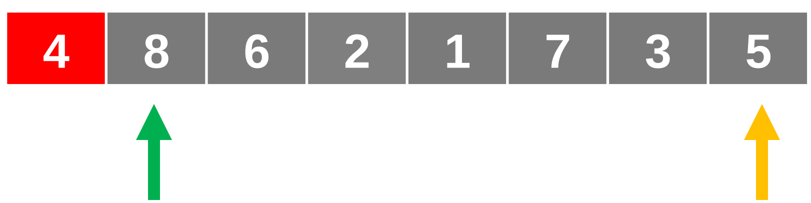

Let's start!

Partitioning: In place (Hoare's)

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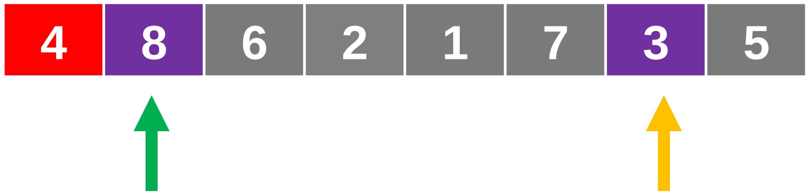

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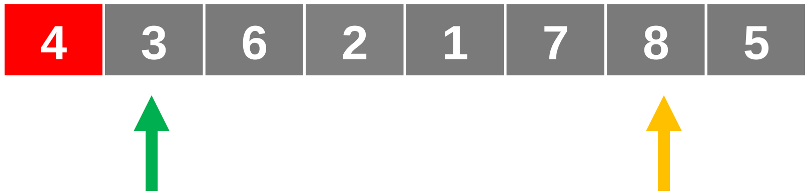

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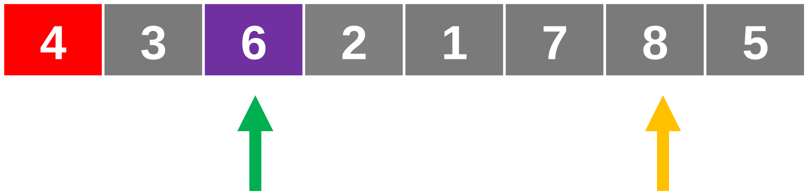

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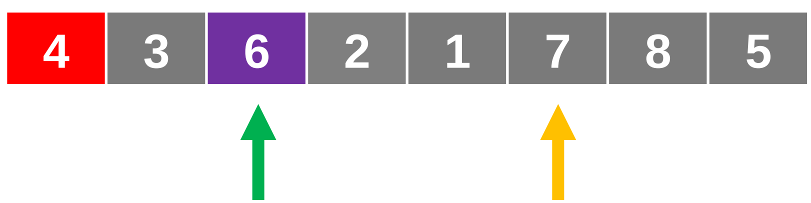

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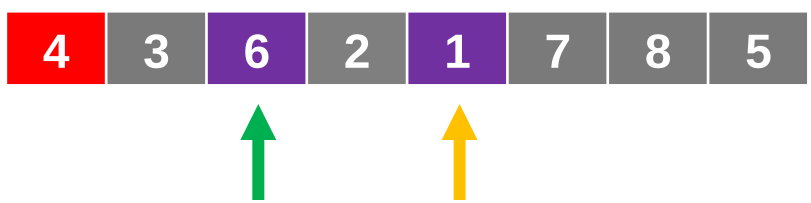

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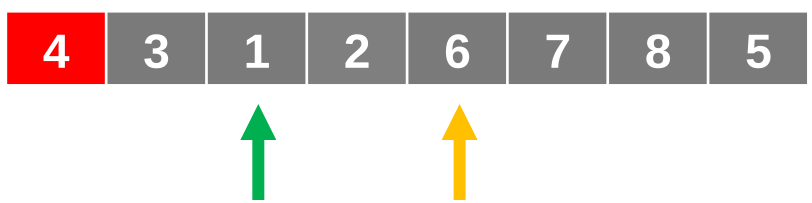

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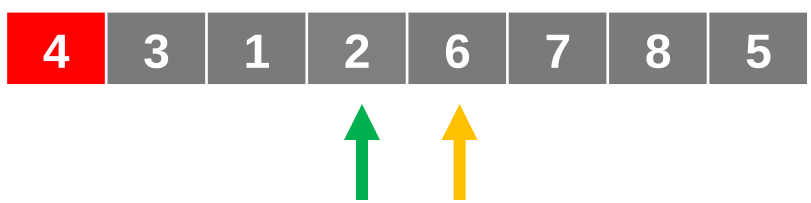

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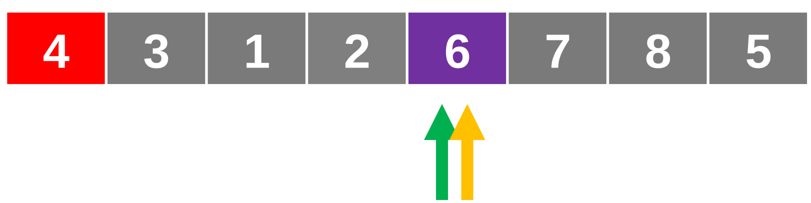

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Swap pivot to the front (position 1)

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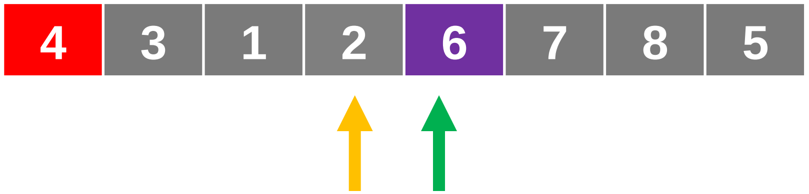

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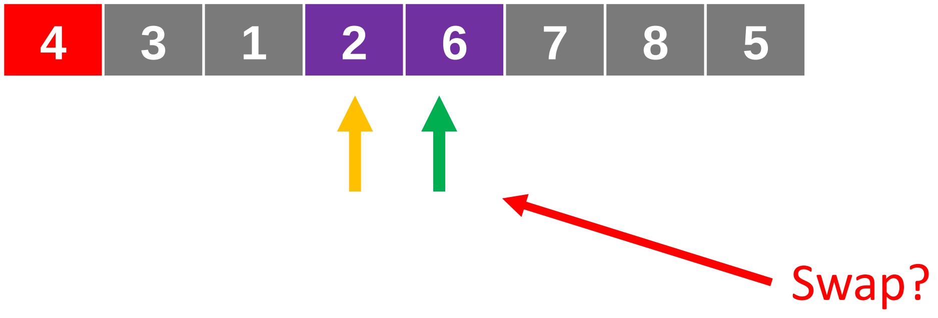

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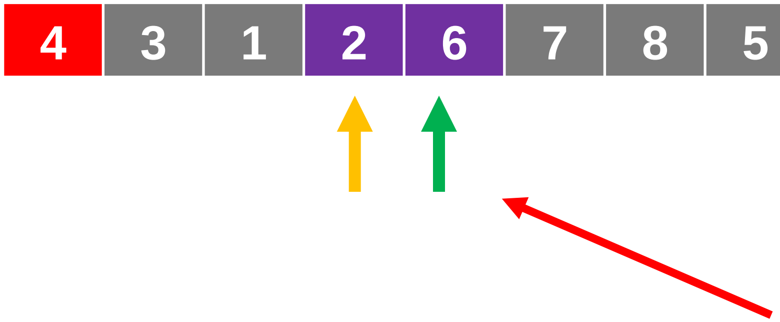

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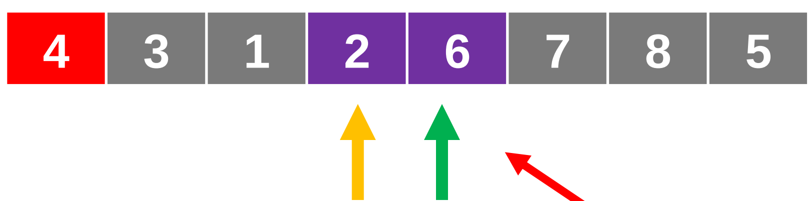

Swap?
NO! It is a bug in the algo
So you know
what to change?

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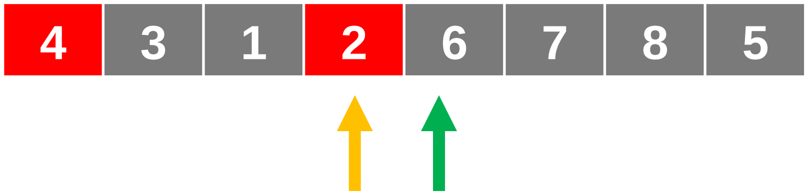

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4 is now in sorted position!

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2	3	1	4	6	7	8	5

Repeat LEFT and RIGHT

Questions?

Quicksort

In-place Partitioning (Hoare’s)

- Invariant?

Quicksort

In-place Partitioning (Hoare's)

- Invariant?
  - L_bad?
  - R_bad?

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Quicksort
In-place Partitioning (Hoare’s)

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Quicksort
In-place Partitioning (Hoare's)

- Invariant?
  - L_bad? Everything to left to L_bad is less/ same than pivot
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  - Between? Not processed yet…

  - What about the pivot? Think about it…

Questions?

Quicksort

In-place Partitioning (Hoare's)

- We want to make it in-place
  - Save memory
- We want to make it fast
  - Avoid copying many items
  - Avoid swapping many times
    - Main focus here: Swap every item only once except pivot
- We want to make it stable
  - Can we?

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MONASH University

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Quicksort

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  - But we know from Tutorial 03 we can make anything stable with memory…

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  - We can add a condition for L_bad and R_bad to help it be stable by using the original index of the pivot with some math…
  - The final swapping of the pivot from 1st position to R_bad would mess up the stability
  - But we know from Tutorial 03 we can make anything stable with memory… but won't be in place…

Questions?

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Quicksort

In-place Partitioning (Hoare's)

- Code it out and see…
  - There is another special edge case that cause this algorithm to fail…
  - Unless you add in a special check =)
  - I might answer this on Slack/ MS Teams later since no interaction for online =(

Questions?

Quicksort

In-place Partitioning (Lomuto’s)

- This is the one you are familiar with
  - From FIT1008

Quicksort

In-place Partitioning (Lomuto's)

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Quicksort

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- Swap each element multiple times

Quicksort
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  - Worse than Hoare's
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Quicksort
In-place Partitioning (Lomuto's)

- This is the one you are familiar with
  - From FIT1008
- In place
- Swap each element multiple times
  - Worse than Hoare's
- … and still unstable
- Easier to understand
- Easier to implement
  - Recall some of the bugs and fail cases I mentioned in Hoare's algorithm shown…

Questions?

Quicksort
Partitioning

- So you now learnt all 3
  - Out-of-place
  - Hoare's
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Quicksort
Partitioning…

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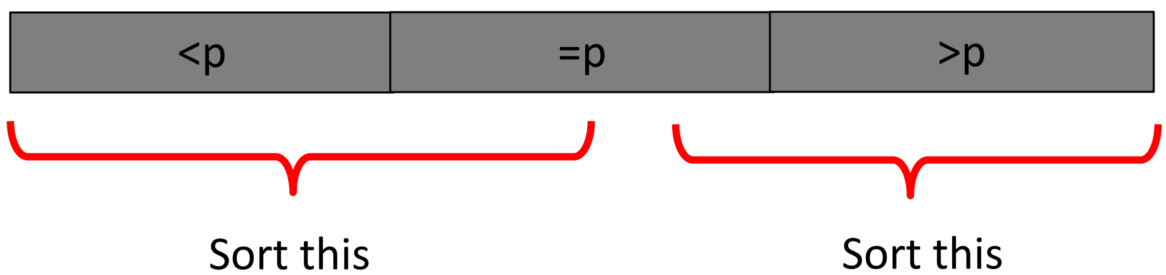

Quicksort
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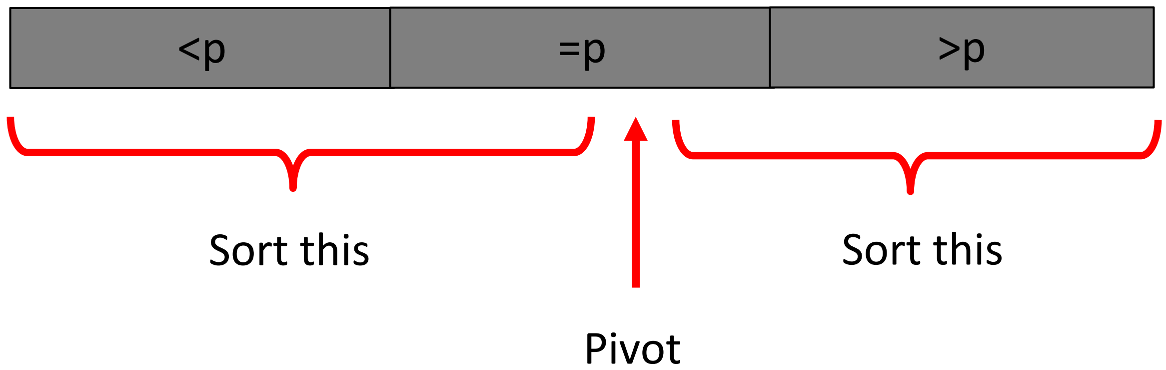

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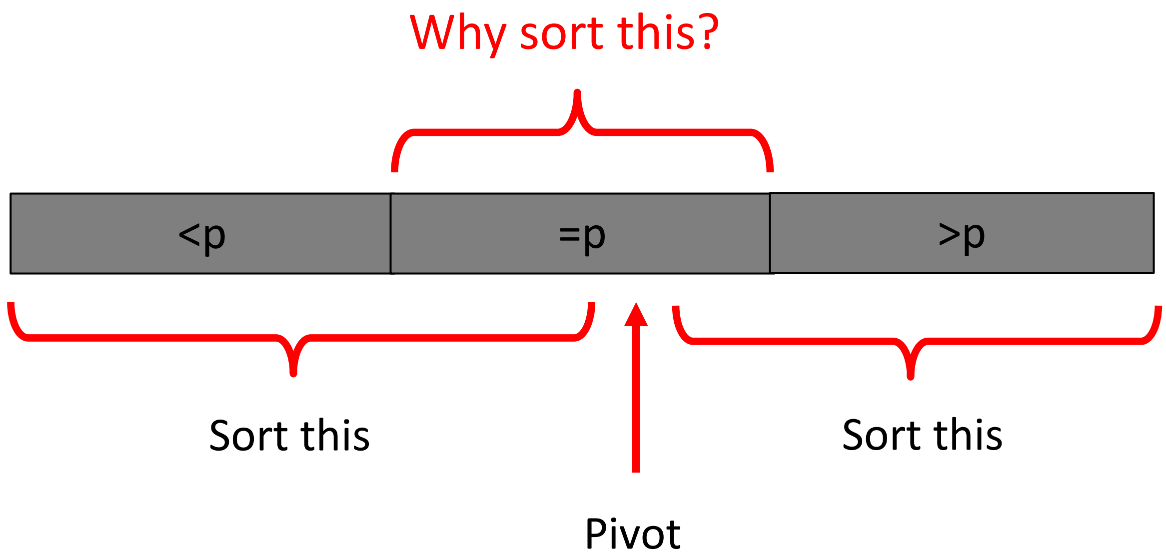

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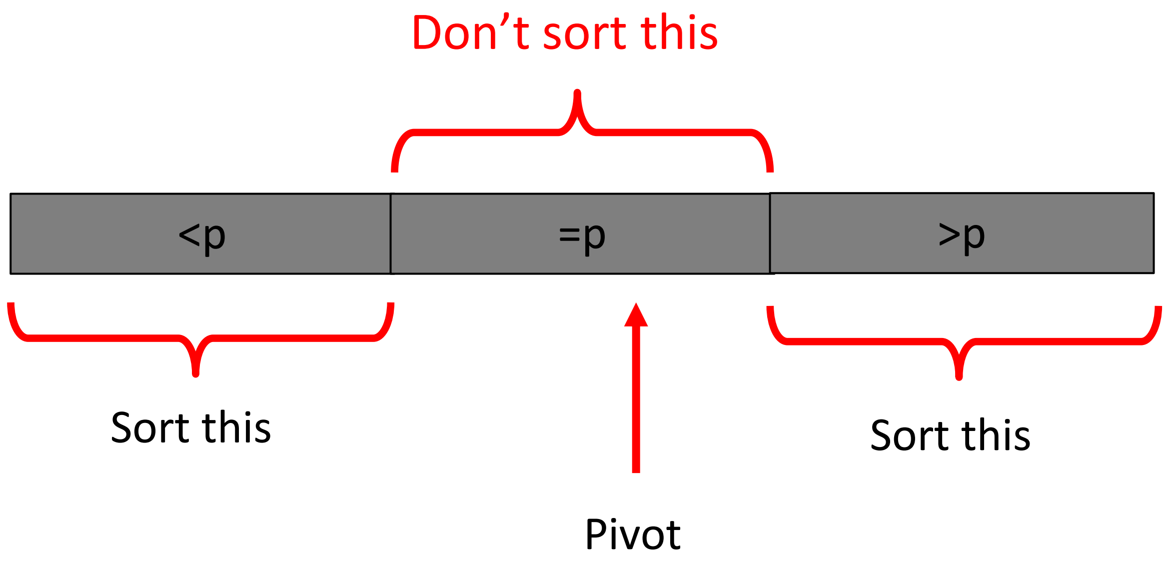

Quicksort

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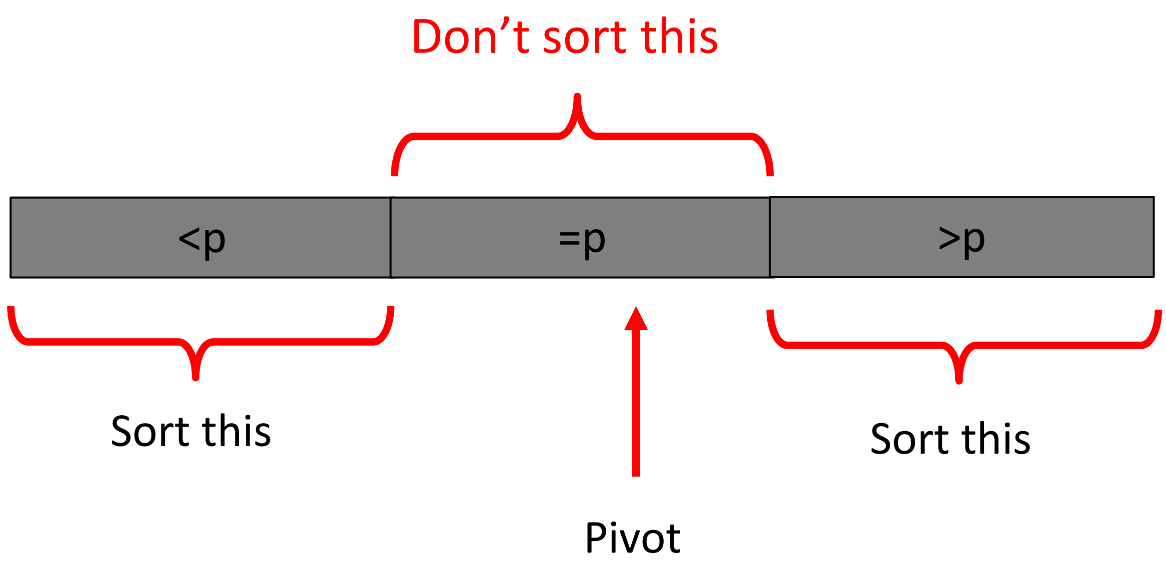

Quicksort
Partitioning…

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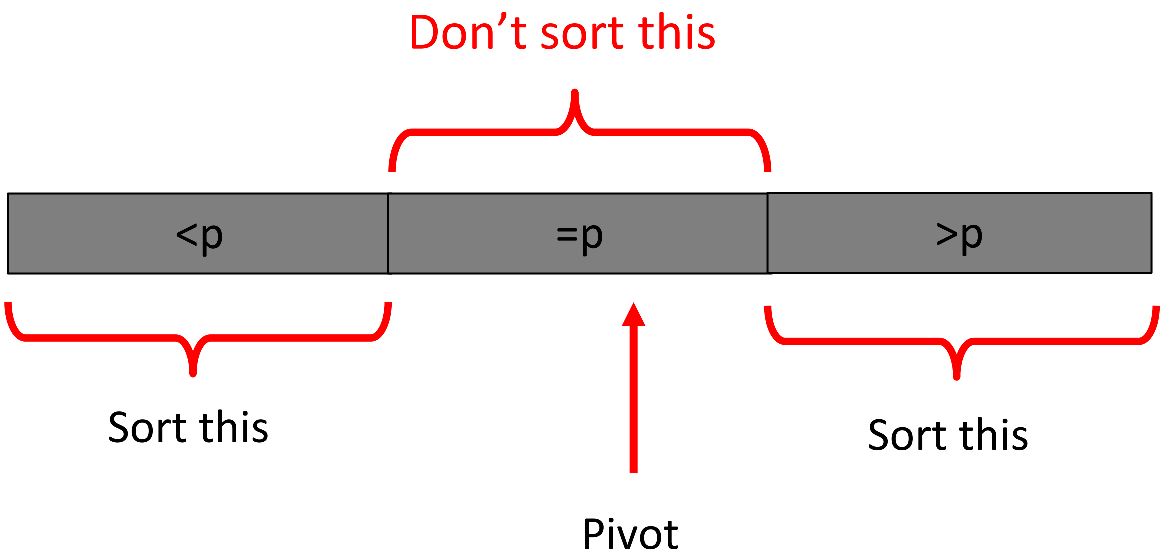
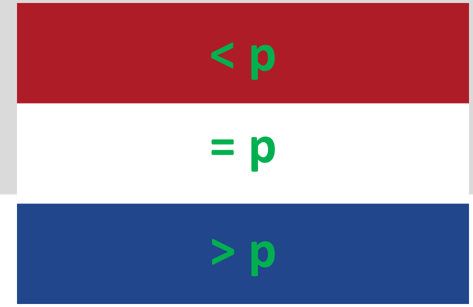


- This lead us to the Dutch national flag problem

Quicksort

Partitioning…



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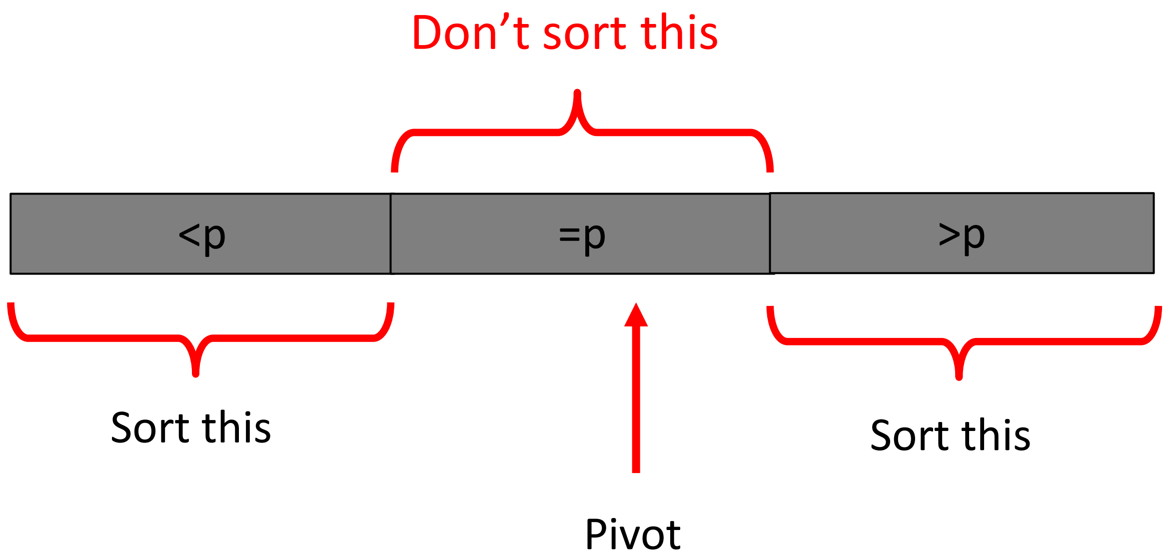

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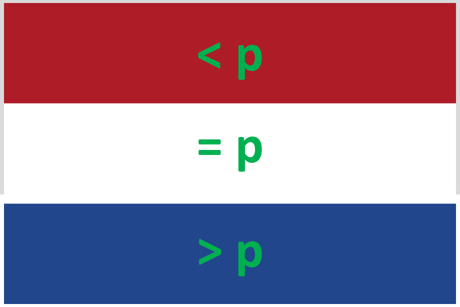
Quicksort
Partitioning…



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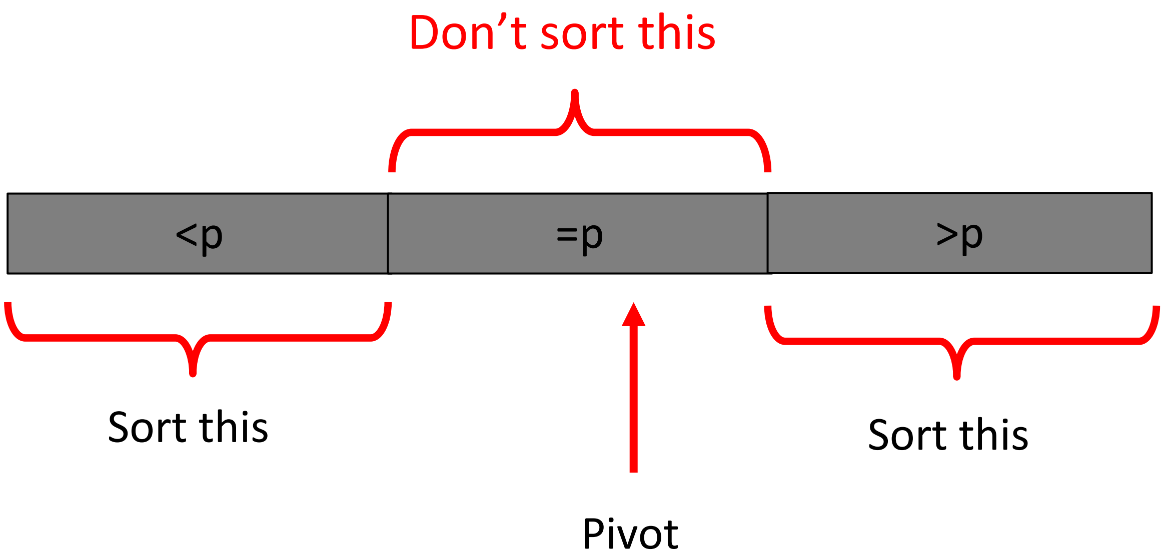


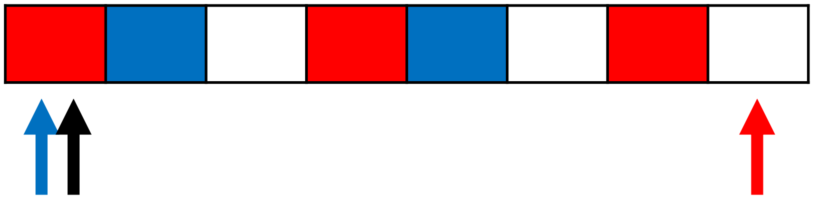
- This lead us to the Dutch national flag problem
  – Let us look at Nathan’s illustration

Dutch National Flag Algoithm

boundary1=1,

j=1

boundary2 = n



Dutch National Flag Algoithm

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boundary1=1,
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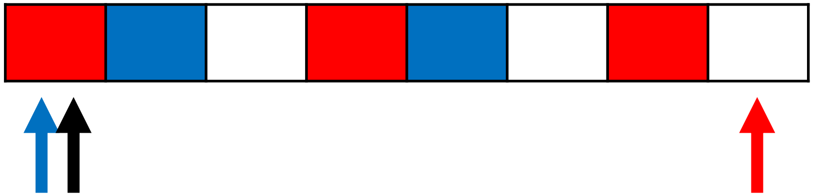

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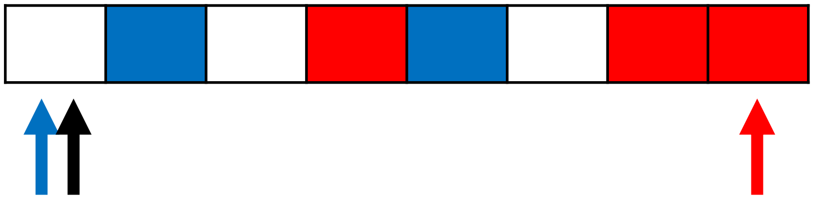

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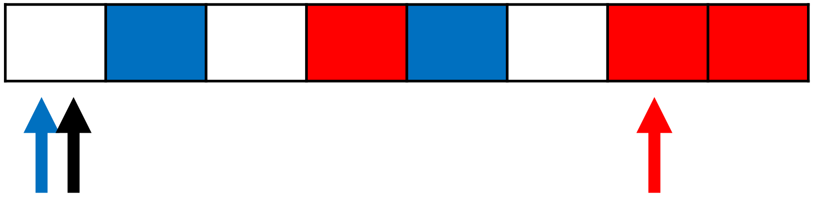

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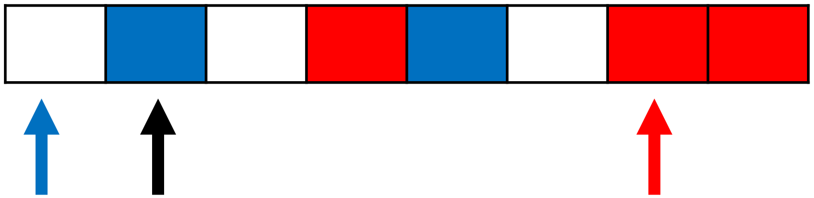

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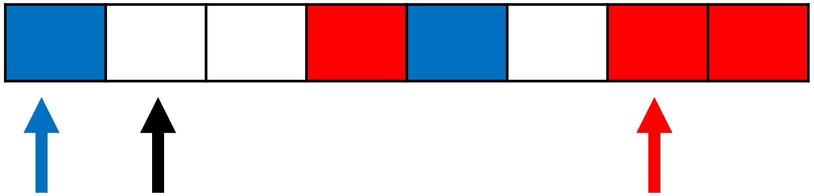

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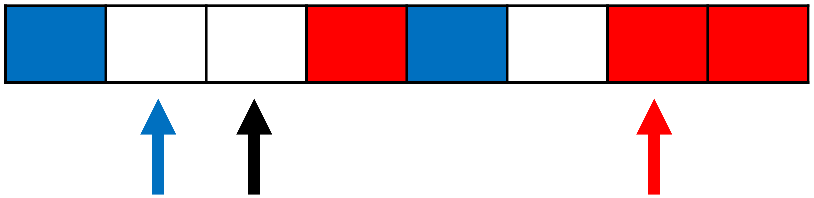

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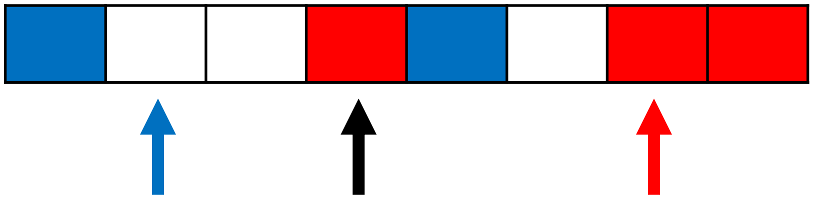

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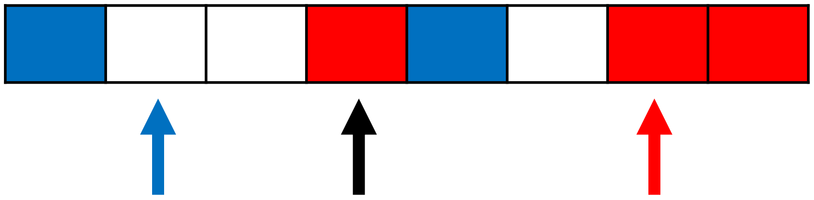

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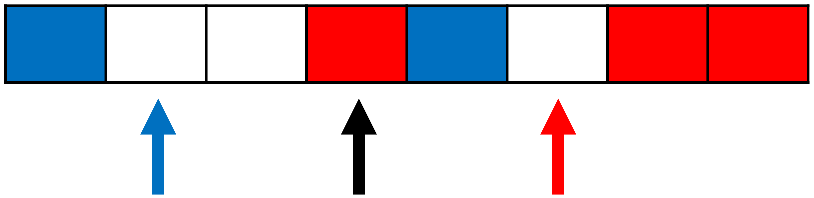

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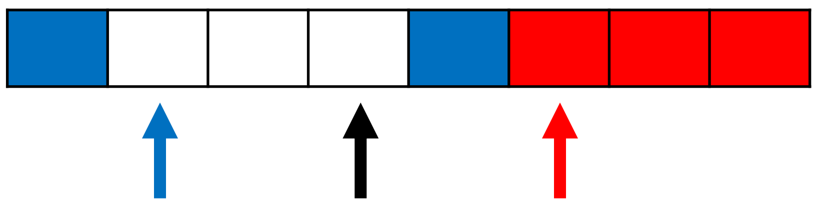

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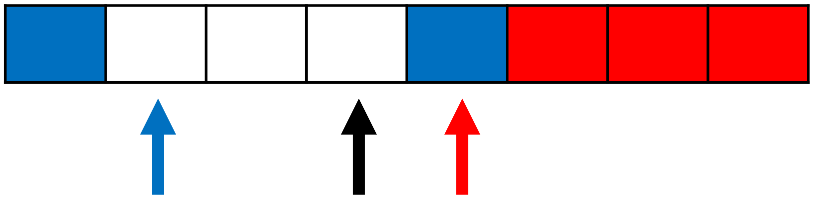

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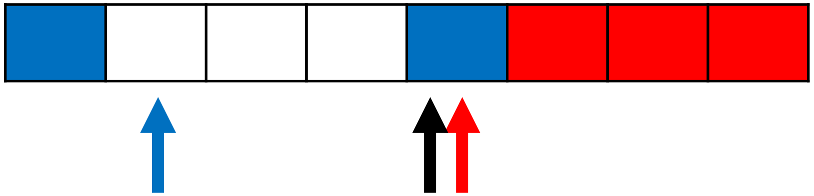

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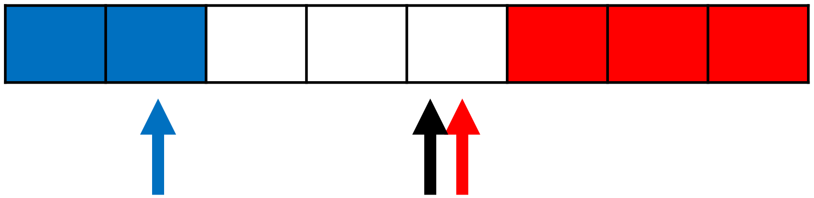

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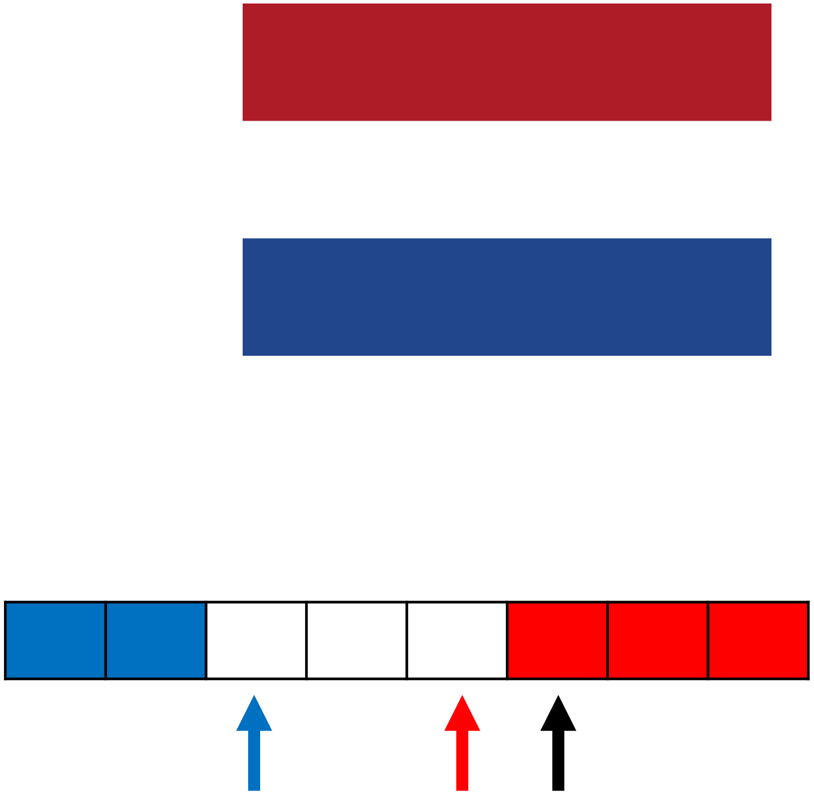

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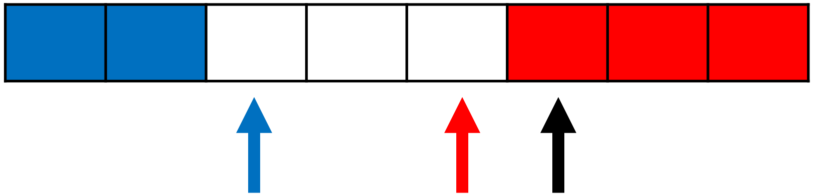

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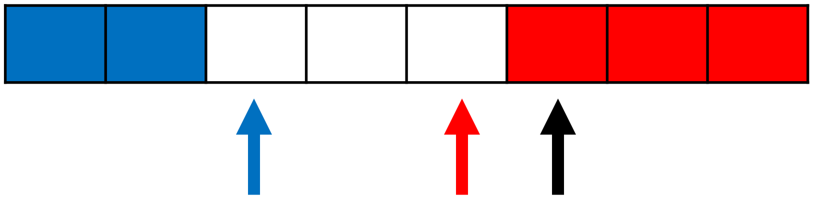

Now quicksort the red and blue parts

Questions?

Dutch Flag

- What are the invariants?
  - List[1…boundary1-1] is blue
  - List[boundary2+1...N] is red
  - List[boundary1…j-1] is white
  - List[j….boundary2] is unprocessed
    - This will be empty when I exit loop at j>boundary2

Quicksort
Dutch Flag

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    - This will be empty when I exit loop at j>boundary2

  - Note it depends if you define boundary1 and boundary2 to be inclusive or exclusive when coding…

  - Code it yourself, there is a specific case which this algorithm still fails
    - You'll need extra if-else in the loop itself

Questions?

Partitioning…

- Minimize swaps
- Minimize work in recursive sort

- Be in-place

Quicksort
Partitioning…

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  - We saw this with Hoare's
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Quicksort

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Quicksort
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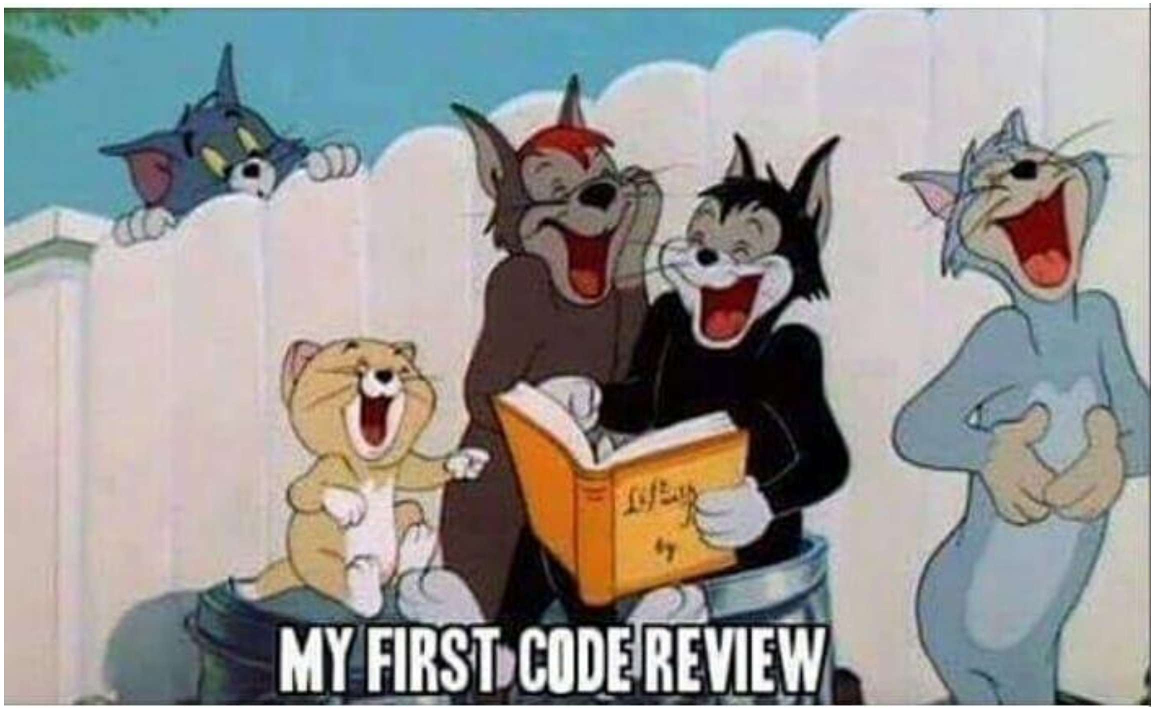
  - Save memory
- Stable?
  - We discuss more in the tutorials…

- Activity, why not we search online together and judge people's quick sort! #CodeReview



Questions?

- Time complexity

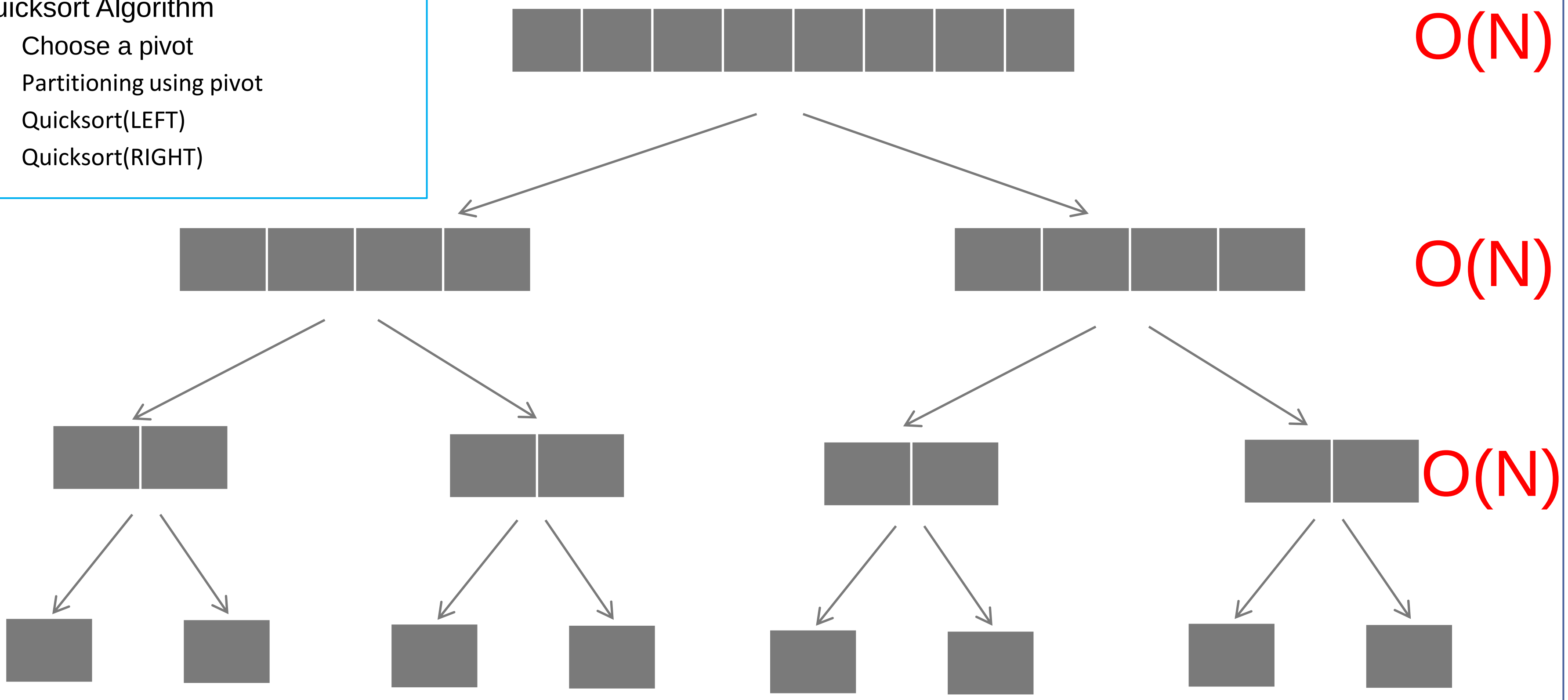
Quicksort
Complexity Analysis

- Time complexity
  - Best
  - Worst

Best-case time complexity

Quicksort Algorithm

- Choose a pivot
- Partitioning using pivot
- Quicksort(LEFT)
- Quicksort(RIGHT)



Best-case Height: O(log N)
Best-case complexity: O(N log N)

Important: Quicksort is not in-place even when in-place partitioning is used. Why?

Recursion depth is at least O(log N)

Worst-case Time Complexity

Quicksort Algorithm

- Choose a pivot
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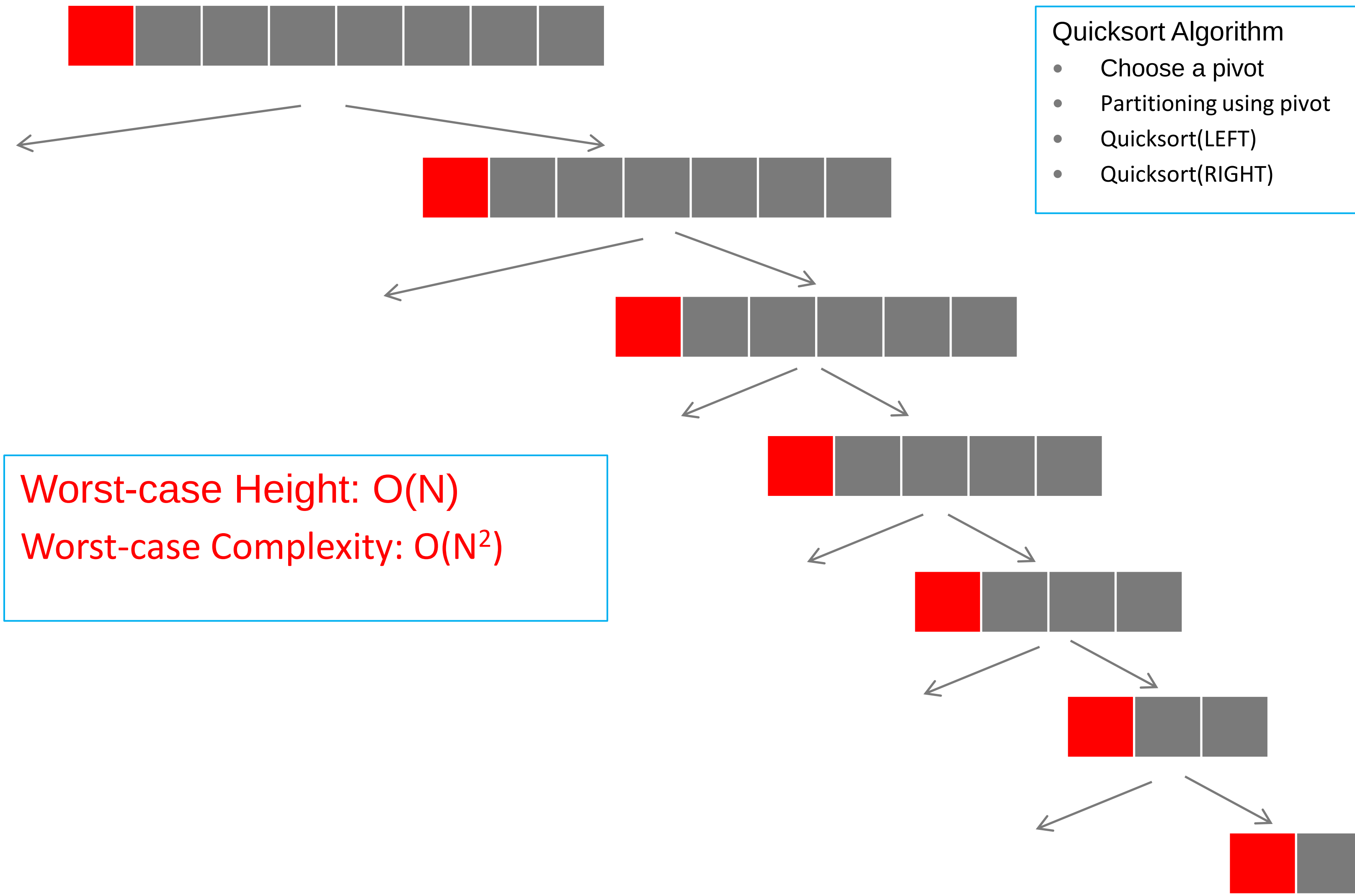

Worst-case Height: O(N)

Worst-case Complexity: $O(N^2)$

Quicksort
Complexity Analysis

- Time complexity
  - Best
  - Worst
  - We all know this from so many discussions in FIT1008

- Time complexity
  - Best
    - When pivot split left-right evenly
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    - When pivot split 1 side (left or right) is empty
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Quicksort

Complexity Analysis

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    - When pivot split left-right evenly
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Questions?

Quicksort
Complexity Analysis

- Or we can use math
  - Like in tutorial

- Or we can use math
  - Like in tutorial
  - Write the recurrence relation for the best case and worst case
    In class activity!

Quicksort
Complexity Analysis

- Or we can use math
  - Like in tutorial
  - Best case

Recurrence relation:

T(1) = b

T(N) = c*N + T(N/2) + T(N/2) = 2*T(N/2) + c*N

Solution (exercise in last week):

O(N log N)

Quicksort
Complexity Analysis

- Or we can use math
  - Like in tutorial
  - Worst case

Recurrence relation:

$$T(1) = b$$

$$T(N) = T(N-1) + c*N$$

Solution:

$$O(N^2)$$

Questions?

Quicksort

Complexity Analysis

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    - This is something I usually prefer to explain by hand in class, let me try here…

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    - When pivot split left-right evenly
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    - When pivot split 1 side (left or right) is empty
    - O(N^2)
    - Probability of this to occur is very very very low
  - We all know this from so many discussions in FIT1008
  - Something new is average complexity…
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    - Why?

Questions?

- Consider a list with N elements

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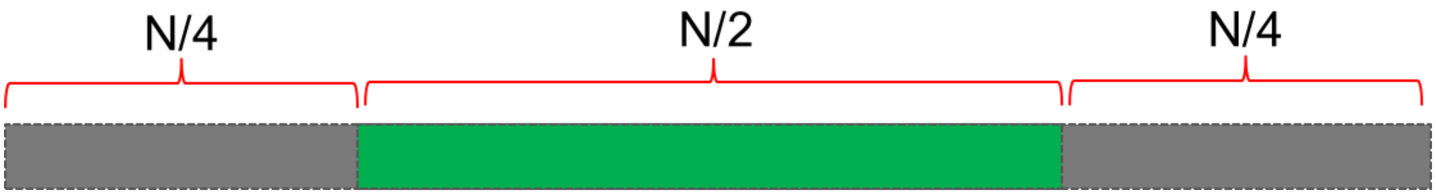

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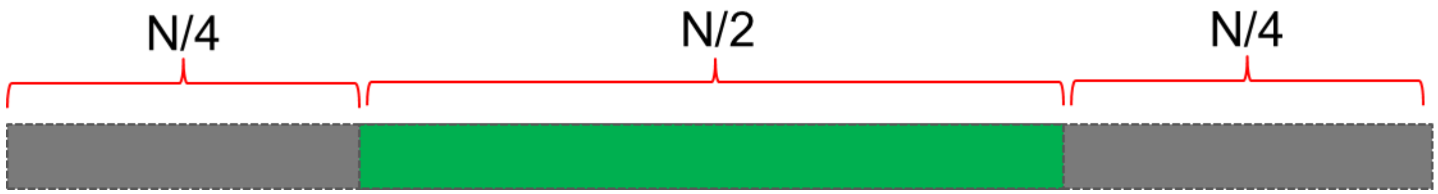

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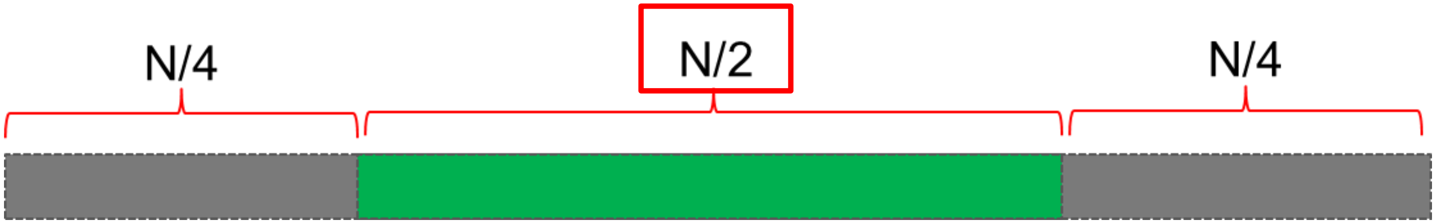

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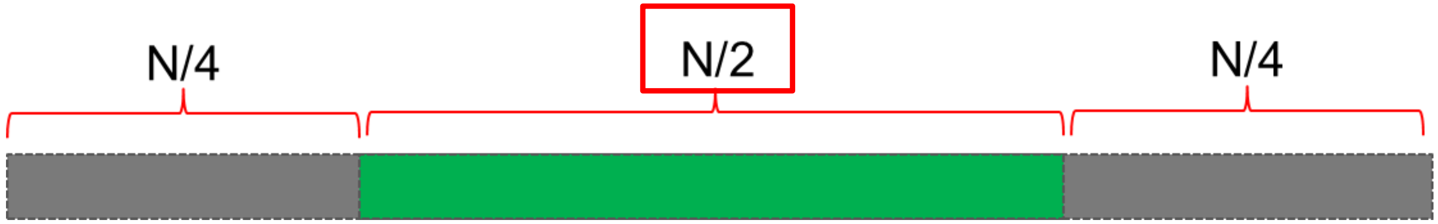

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  - Worst case in grey area?

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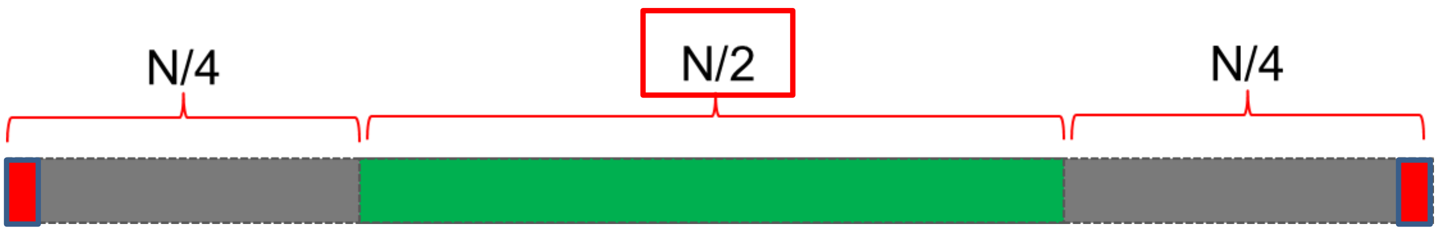

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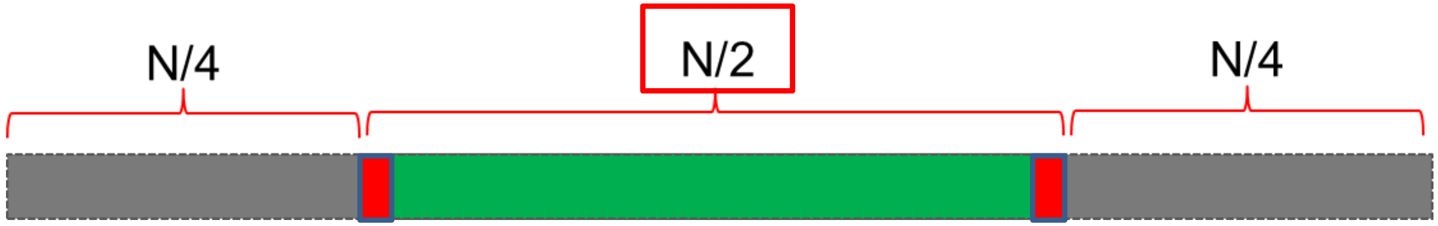

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Quicksort
Complexity Analysis

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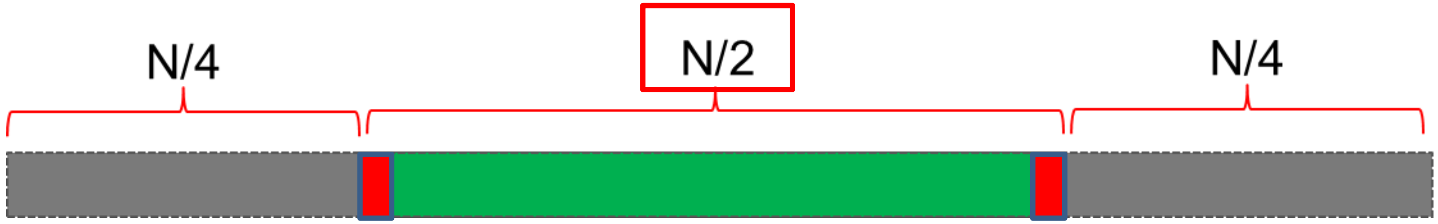

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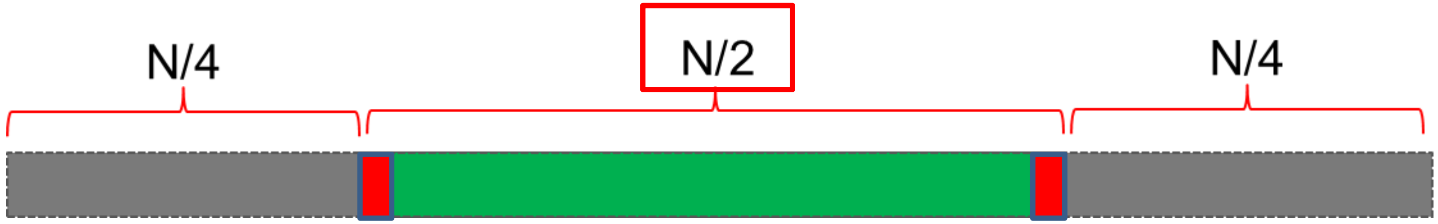

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Quicksort
Complexity Analysis

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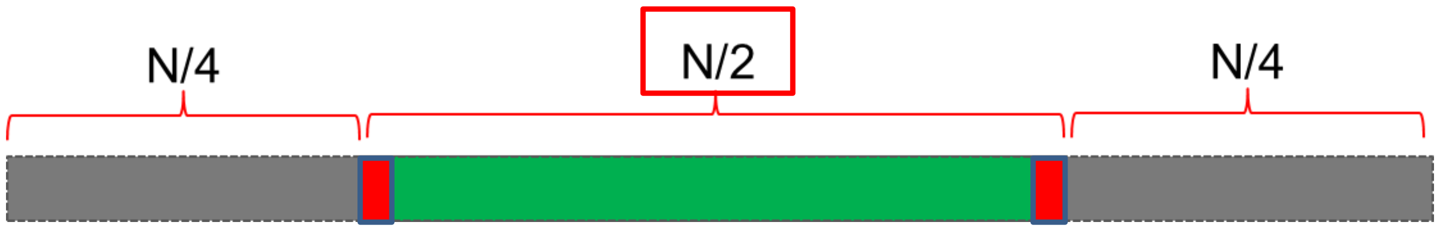

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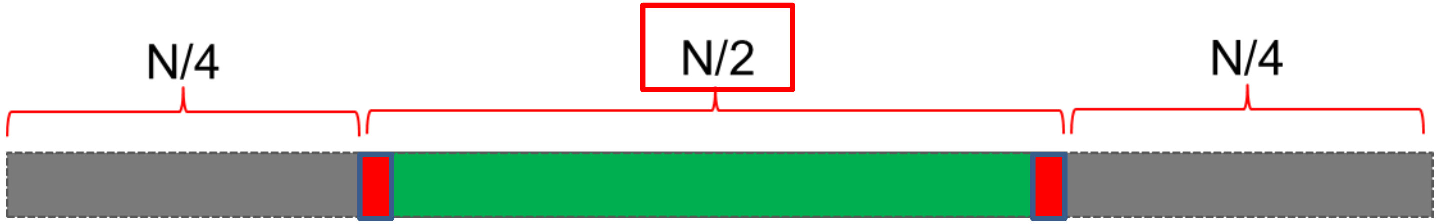

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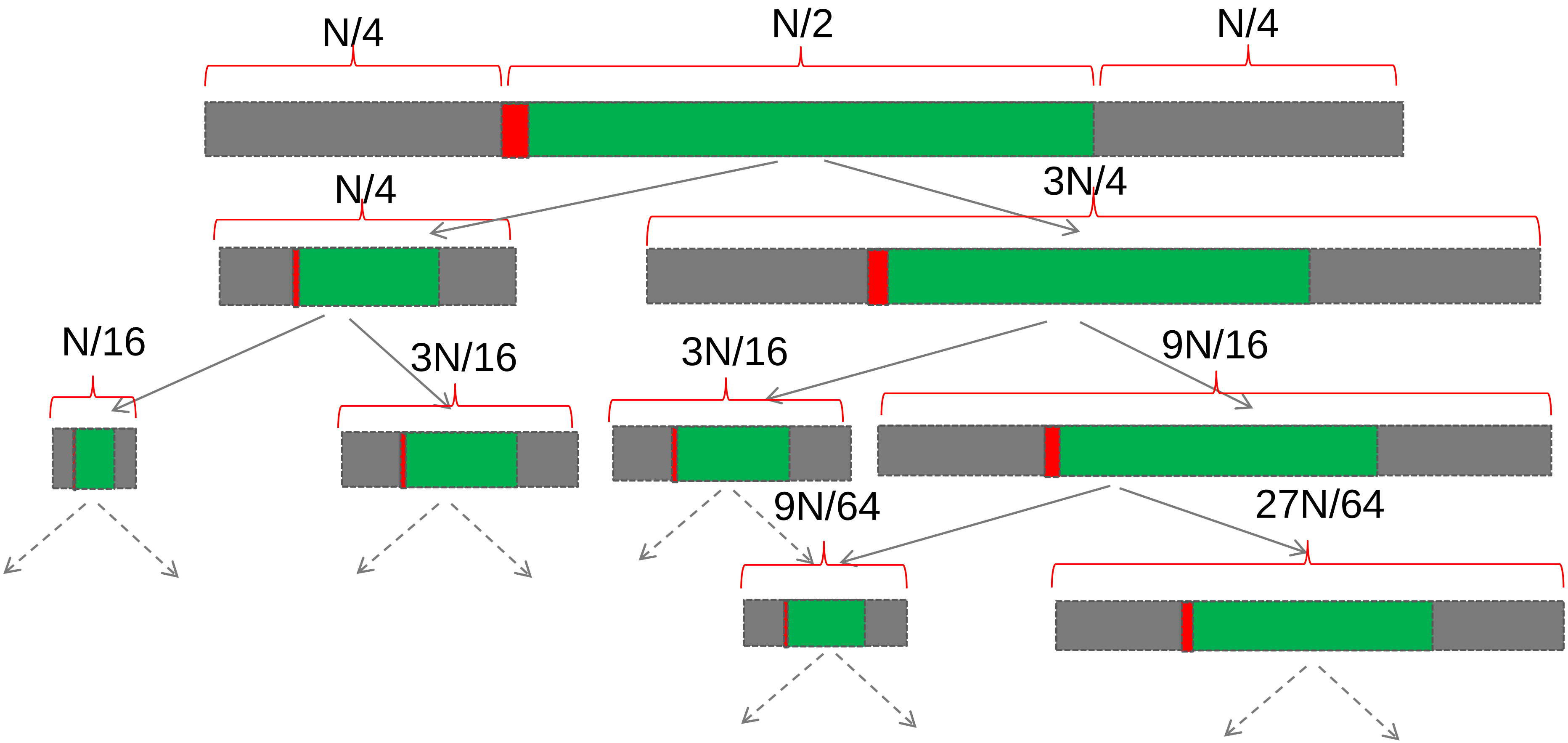
- So we calculate what is h

- Let us just do the normal drawing



Quicksort
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Quicksort

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  - Our maximum depth for average case is 2h
    - If within green always it is h
    - But it isn't always green, so it can be more than h (by some factor)
    - But since we have a 50% chance at each level
    - We can just average it out to 2h

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  - Therefore, average case height is O(log N)
  - Each level have a partition cost of O(N)
  - Total average cost is O(N log N) ⟵ But it isn't base 2 for log?

Average case Time complexity

- Therefore, height in average case is O(log N)
- Like before, the cost at each level is O(N)
- The average case complexity is thus O(N log N)

Does $O(\log_a N) = O(\log_b N)$ if a and b are constants?

Change of base rule: $\log_a N = \dfrac{\log_b N}{\log_b a}$

So the base of the log doesn't matter for complexity (though it does in practice)

Questions?

- Can be done with math as well
  - Just like best case and worst case

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  - Just like best case and worst case
  - Just that it is really painful to do… and thus not examinable

Average-case complexity using recurrence
(NOT EXAMINABLE)

Recurrence relation:

T(N) = ???

- For simplicity, assume partitioning costs (N+1) operations
- Assume pivot is at index k

$T_k(N) = (N+1) + T(N-k) + T(k-1)$

- Average cost is the average for k being from 1 to N

$$T(N) = \frac{\sum_{k=1}^{N} T_k(N)}{N}$$

$$T(N) = (N+1) + \frac{\sum_{k=1}^{N} T(N-k) + T(k-1)}{N}$$

$$T(N) = (N+1) + \frac{2}{N}\sum_{k=1}^{N} T(k-1)$$

T(N-1)	T(0)
T(N-2)	T(1)
T(N-3)	T(2)
…	…
	T(N-3)
	T(N-2)
	T(N-1)

Quicksort Algorithm
- Choose a pivot
- Partitioning using pivot
- Quicksort(LEFT)
- Quicksort(RIGHT)

$$\sum_{k=1}^{N} T(N-k) = \sum_{k=1}^{N} T(k-1)$$

Average-case complexity using recurrence
(NOT EXAMINABLE)

Recurrence relation:

T(1) = b

Multiplying N on both sides

$$T(N) = (N+1) + \frac{2}{N}\sum_{k=1}^{N} T(k-1)$$

$$N.T(N) = N(N+1) + 2\sum_{k=1}^{N} T(k-1) \longrightarrow \text{(A)}$$

$$(N-1).T(N-1) = N(N-1) + 2\sum_{k=1}^{N-1} T(k-1) \longrightarrow \text{(B)}$$

$$N.T(N) - (N-1).T(N-1) = 2N + 2T(N-1)$$

(A) – (B)

$$N.T(N) = 2N + 2T(N-1) + (N-1).T(N-1) = 2N + (N+1).T(N-1)$$

Simplify

$$T(N) = 2 + \frac{N+1}{N} T(N-1)$$

Divide both sides by N

Average-case complexity using recurrence
(NOT EXAMINABLE)

Recurrence relation:

T(1) = b

$$T(N) = 2 + \frac{N+1}{N} T(N-1) \longrightarrow \text{(A)}$$

Let's solve it:

$$T(N-1) = 2 + \frac{N}{N-1} T(N-2)$$

Cost for T(N-1)

Replace T(N-1) in (A)

$$T(N) = 2 + \frac{N+1}{N}\left(2 + \frac{N}{N-1} T(N-2)\right) = 2 + \frac{2(N+1)}{N} + \frac{N+1}{N-1} T(N-2) \longrightarrow \text{(B)}$$

$$T(N-2) = 2 + \frac{N-1}{N-2} T(N-3)$$

Cost for T(N-2)

Replace T(N-2) in (B)

$$T(N) = 2 + \frac{2(N+1)}{N} + \frac{2(N+1)}{N-1} + \frac{2(N+1)}{N-2} T(N-3)$$

$$T(N) = 2 + \frac{2(N+1)}{N} + \frac{2(N+1)}{N-1} + \frac{2(N+1)}{N-2} + \ldots + \frac{2(N+1)}{N-k+2} + \frac{2(N+1)}{N-k+1} T(N-k)$$

See the pattern for k?

Average-case complexity using recurrence
(NOT EXAMINABLE)

Recurrence relation:

T(1) = b $$T(N) = 2 + \frac{N+1}{N} T(N-1)$$

Let's solve it:

$$T(N) = 2 + \frac{2(N+1)}{N} + \frac{2(N+1)}{N-1} + \frac{2(N+1)}{N-2} + \ldots + \frac{2(N+1)}{N-k+2} + \frac{2(N+1)}{N-k+1} T(N-k)$$

N-k =1 → k = N-1

$$T(N) = 2 + \frac{2(N+1)}{N} + \frac{2(N+1)}{N-1} + \frac{2(N+1)}{N-2} + \ldots + \frac{2(N+1)}{3} + \frac{2(N+1)}{2} T(1)$$

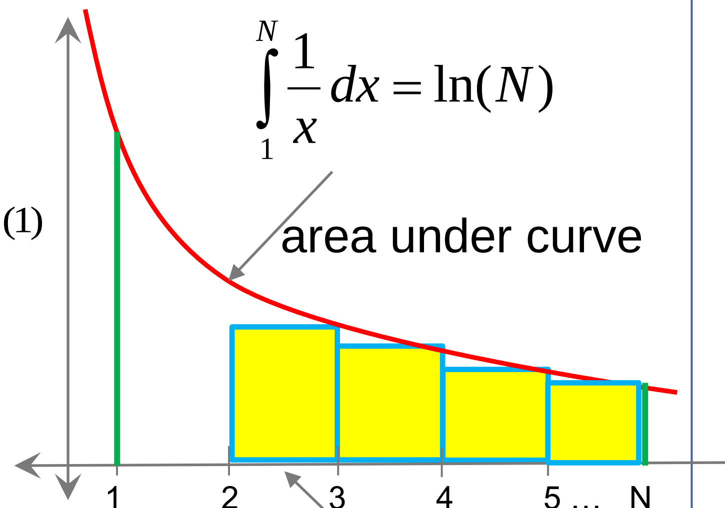
Simplify

$$T(N) = 2 + 2(N+1)\left(\frac{1}{N} + \frac{1}{N-1} + \frac{1}{N-2} + \ldots + \frac{1}{3}\right) + b(N+1)$$

$$T(N) = 2 + b(N+1) + 2(N+1)\sum_{k=3}^{N} \frac{1}{k}$$

$$T(N) < 2 + b(N+1) + 2(N+1)\ln(N)$$

T(N) = O (N log N)



$$\int_1^N \frac{1}{x} dx = \ln(N)$$

Area of rectangles

$$\sum_{k=3}^{N} \frac{1}{k}$$

$$\sum_{k=3}^{N} \frac{1}{k} < \ln(N)$$

Questions?

Quick Sort
Summary

- Good sorting algorithm
  - Using divide and conquer

Quick Sort

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  - Everything depends on pivot! Next lecture on how to select pivot

Questions?

Thank You