

FIT2004

Algorithms and Data Structures

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Referencing materials by
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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?
 - Divide and conquer



pivot

Quicksort

Brief description

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

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?
 - Divide and conquer
- Partition-based on the pivot
 - **Smaller or equal** to the left of pivot
 - **Bigger** to the right of pivot


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

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
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- 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
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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

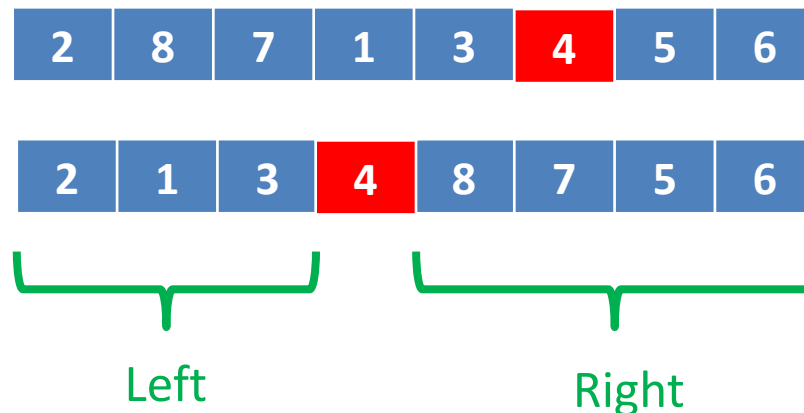
- Given a list
- Choose a **pivot** (doesn't matter which)

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

Quicksort

Example

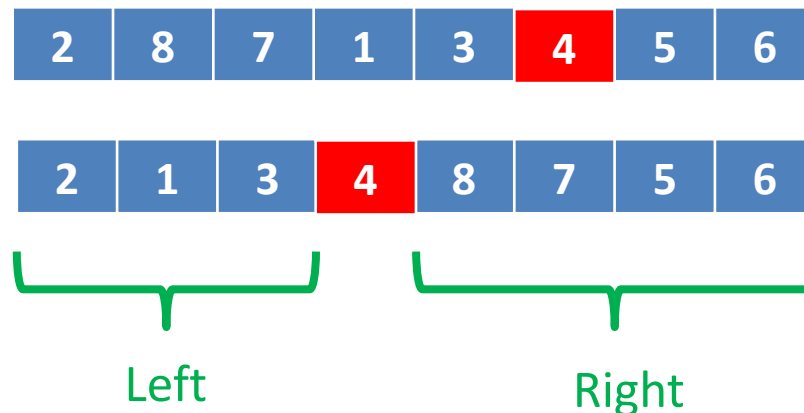
- Given a list
- Choose a **pivot** (doesn't matter which)
- Ensure invariant
 - Left \leq pivot
 - Right $>$ pivot



Quicksort

Example

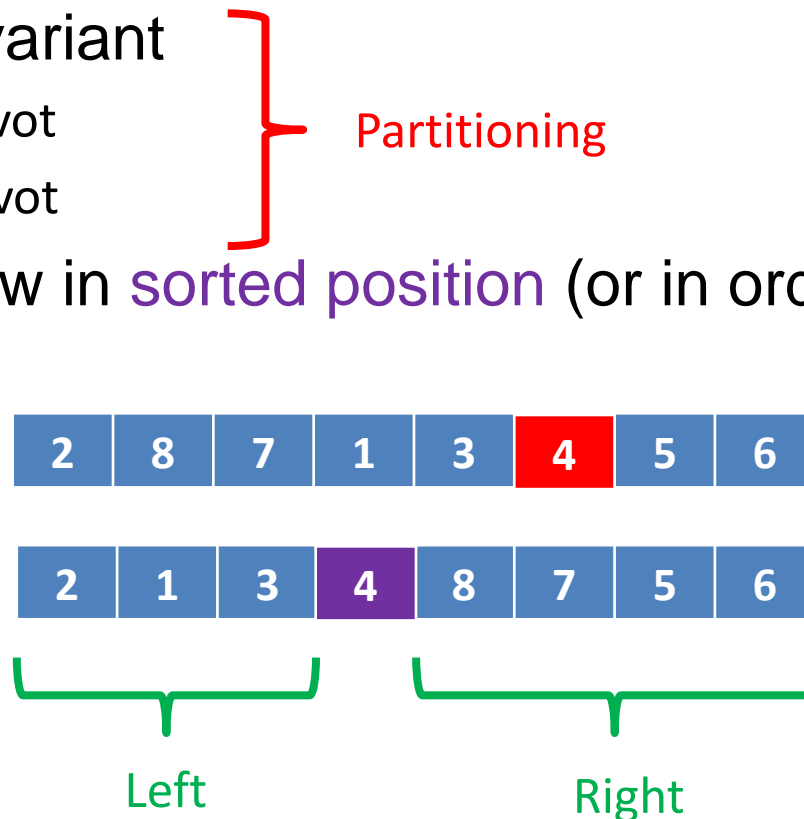
- Given a list
 - Choose a **pivot** (doesn't matter which)
 - Ensure invariant
 - Left \leq pivot
 - Right $>$ pivot
- } Partitioning



Quicksort

Example

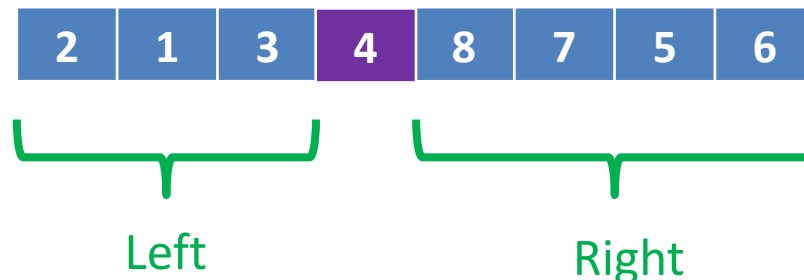
- Given a list
- Choose a **pivot** (doesn't matter which)
- Ensure invariant
 - Left \leq pivot
 - Right $>$ pivot
- Pivot is now in **sorted position** (or in order)



Quicksort

Example

- Given a list
 - Choose a **pivot** (doesn't matter which)
 - Ensure invariant
 - Left \leq pivot
 - Right $>$ pivot
- } Partitioning
- Pivot is now in **sorted position** (or **in order**)
 - Then we repeat for **left** and **right**



Quicksort

Example

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

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- Given a list
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Quicksort

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- Given a list
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Quicksort

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 - Choose a **pivot** (doesn't matter which)
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 - Choose a **pivot** (doesn't matter which)
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Quicksort

Example

- Given a list
 - Choose a **pivot** (doesn't matter which)
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- Pivot is now in **sorted position** (or in order)
 - Then we repeat for **left** and **right**



Quicksort

Example

- Given a list
- Choose a **pivot** (doesn't matter which)
- Ensure invariant
 - Left \leq pivot
 - Right $>$ pivot
- Pivot is now in **sorted position** (or in order)
- Then we repeat for **left** and **right**
- Till **sorted**

} Partitioning

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

Questions?

Quicksort

Partitioning

- What is partitioning?

Quicksort

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

Quicksort

Partitioning

- What is partitioning?
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 - Here, mainly the left and the right
- 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?

Quicksort

Out-of-place Partitioning

- Not in-place



Quicksort

Out-of-place Partitioning

- Not in-place

not $O(1)$ auxiliary space



LEFT

RIGHT

Quicksort

Out-of-place Partitioning

- Not in-place



$O(2n)$
 $O(n)$

LEFT
RIGHT

Quicksort

Out-of-place Partitioning

- Not in-place



LEFT
RIGHT



Quicksort

Out-of-place Partitioning

- Not in-place



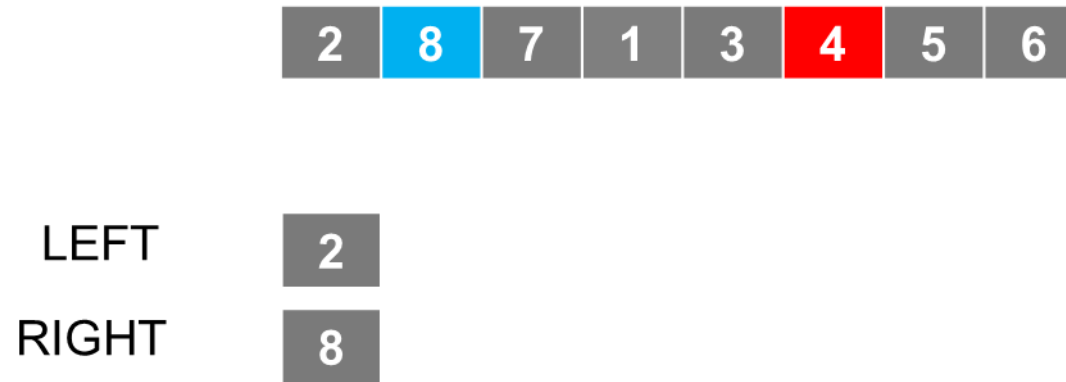
LEFT
RIGHT



Quicksort

Out-of-place Partitioning

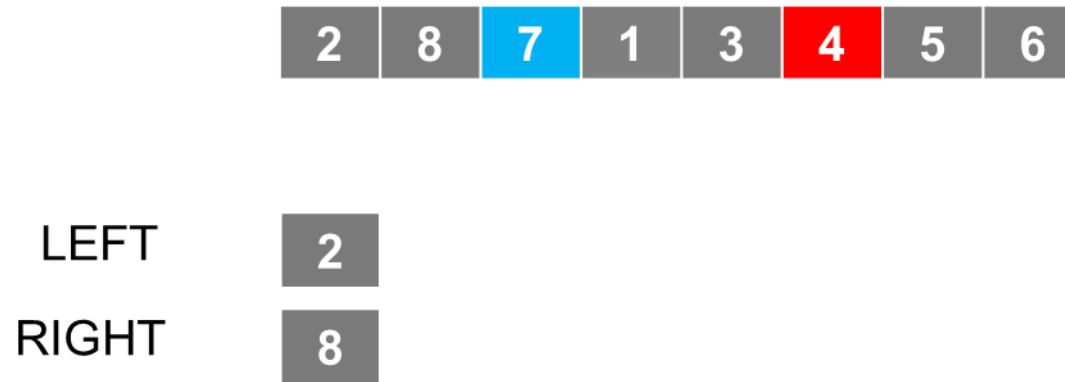
- Not in-place



Quicksort

Out-of-place Partitioning

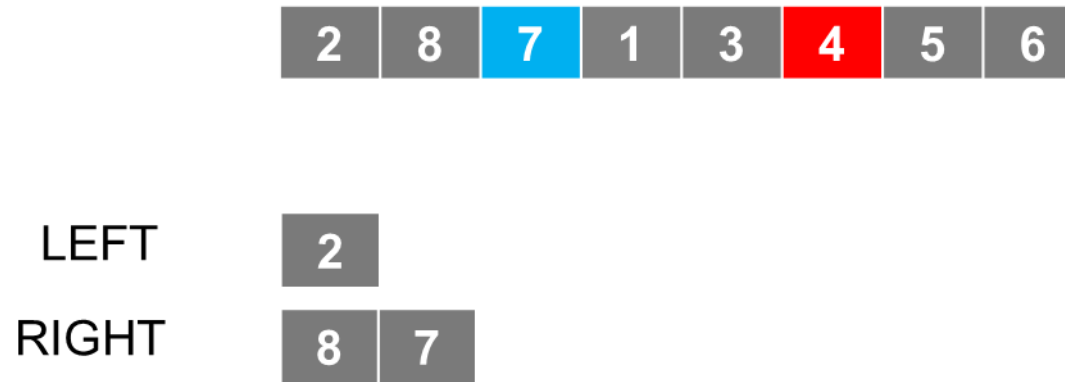
- Not in-place



Quicksort

Out-of-place Partitioning

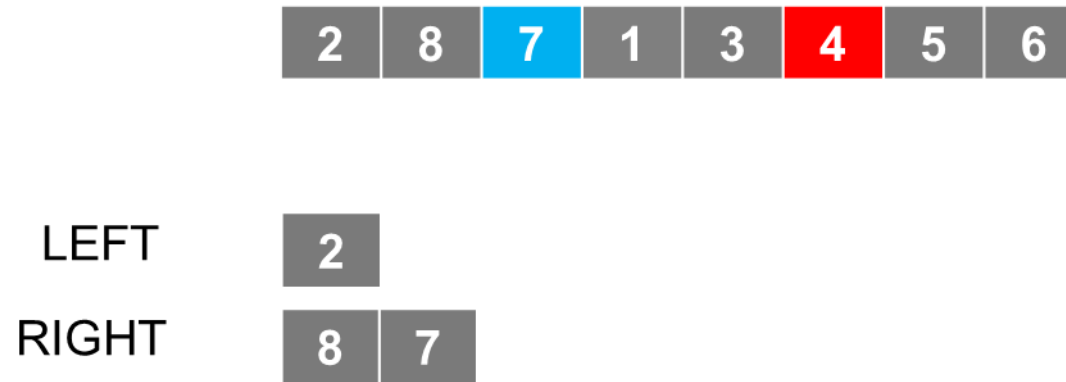
- Not in-place



Quicksort

Out-of-place Partitioning

- Not in-place



Quicksort

Out-of-place Partitioning

- Not in-place

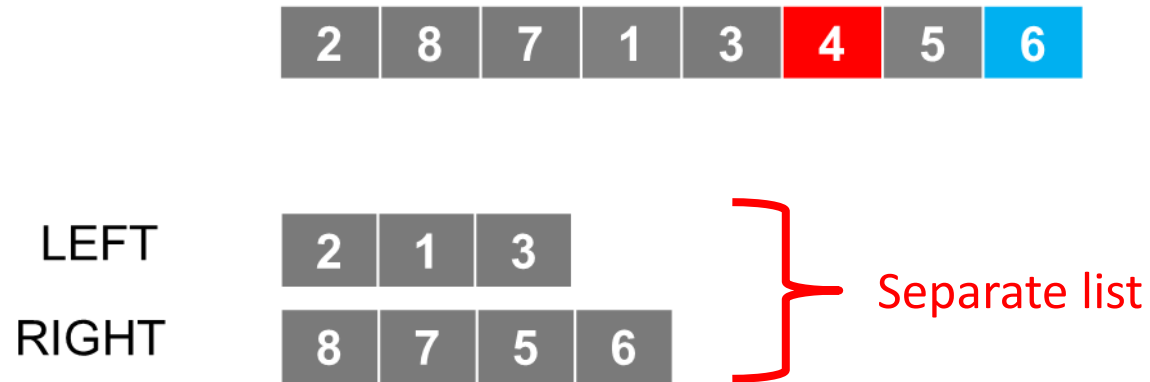


Repeat till last element

Quicksort

Out-of-place Partitioning

- Not in-place



Quicksort

Out-of-place Partitioning

- Not in-place



LEFT

RIGHT



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



- 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



- Is the algorithm stable?
 - \leq 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



- Is the algorithm stable?
 - \leq 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



- Is the algorithm stable? **NO**
 - \leq pivot to the left: **everything \neq 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



- Is the algorithm stable? **NO**
 - \leq pivot to the left: **everything \leq 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

- Not in-place

- Need left temporary list
- Need right temporary list
- Combined back to the original list



$O(N)$ additional space
beside recursive stack



LEFT

RIGHT

- Is the algorithm stable? **NO** with enough memory can make all sorting stable remain stable by maintain relative order of the same values in the list
 - \leq 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?

Quicksort

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

- 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

- 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

Quicksort

In-place Partitioning (Hoare's)

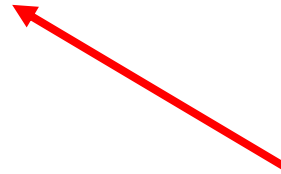
- We want to make it in-place
 - Save memory
- We want to make it fast
 - Avoid copying many items
 - Avoid swapping many times
- We want to make it stable
 - Can we?

- 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?

- 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



Pointers used for
swapping

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. $> \text{pivot}$

move R_bad left until we find a “bad” element, i.e. $< \text{pivot}$

swap these elements

$< =$



Partitioning: In place (Hoare's)

Swap pivot to the front (position 1)

$L_bad = 2$, $R_bad = N$

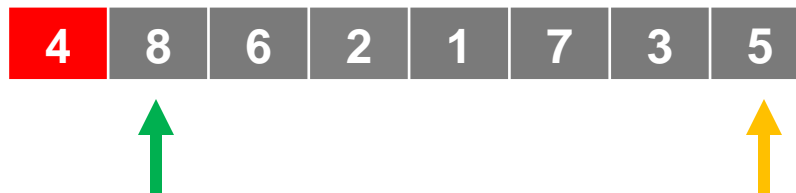
Repeat until L_bad and R_bad cross

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 \leq pivot
right $>$ pivot

Partitioning: In place (Hoare's)

Swap pivot to the front (position 1)

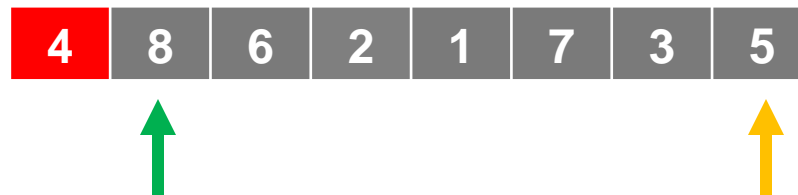
$L_bad = 2$, $R_bad = N$

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

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



Let's start!

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)

$L_bad = 2$, $R_bad = N$

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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)

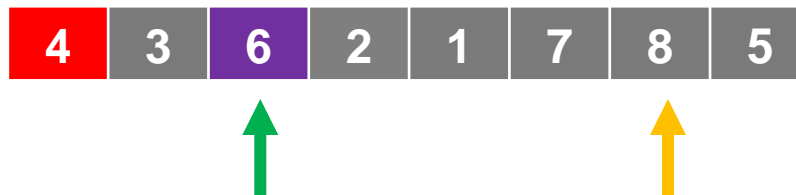
$L_bad = 2$, $R_bad = N$

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



Partitioning: In place (Hoare's)

Swap pivot to the front (position 1)

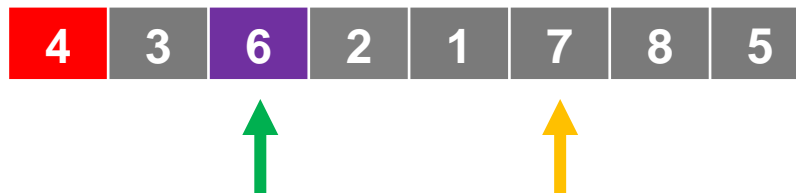
L_bad = 2, R_bad = N

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)

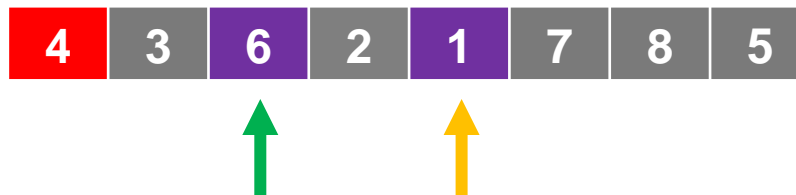
$L_bad = 2$, $R_bad = N$

Repeat until L_bad and R_bad cross

move L_bad right until we find a “bad” element, i.e. $>$ pivot

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swap these elements



Partitioning: In place (Hoare's)

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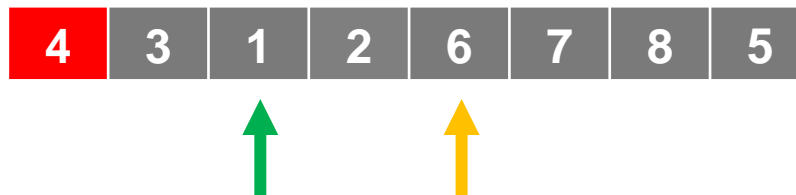
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Partitioning: In place (Hoare's)

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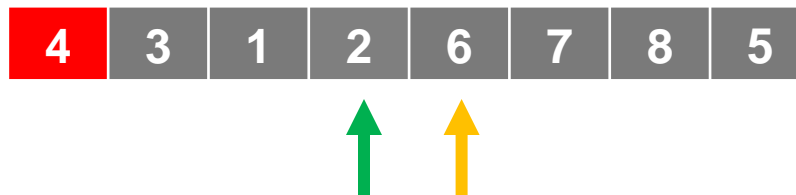
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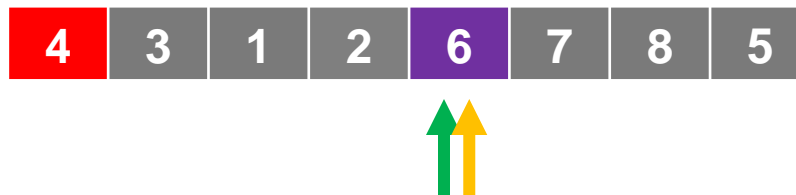
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Partitioning: In place (Hoare's)

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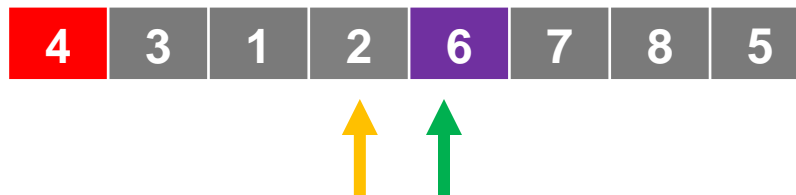
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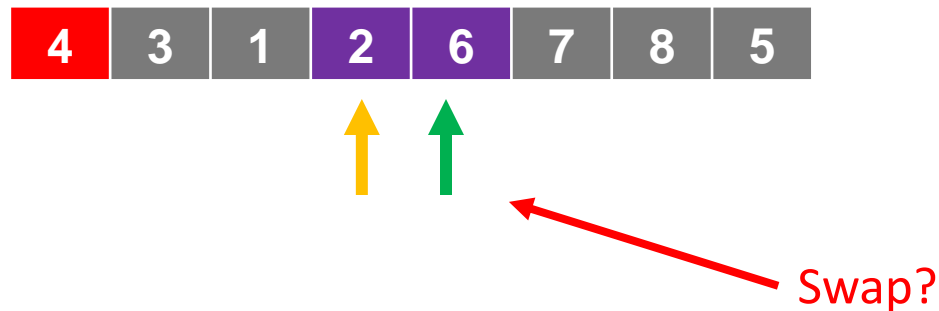
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swap these elements

swap pivot to R_bad



Partitioning: In place (Hoare's)

Swap pivot to the front (position 1)

$L_bad = 2$, $R_bad = N$

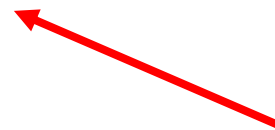
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swap these elements

swap pivot to R_bad



Swap?

NO! It is a bug in the algo

Partitioning: In place (Hoare's)

Swap pivot to the front (position 1)

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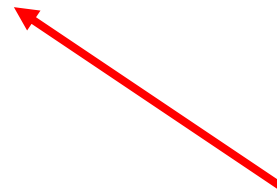
Repeat until L_bad and R_bad cross

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swap these elements

swap pivot to R_bad



Swap?

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

Partitioning: In place (Hoare's)

Swap pivot to the front (position 1)

$L_bad = 2$, $R_bad = N$

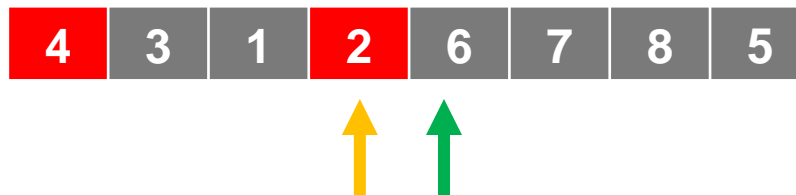
Repeat until L_bad and R_bad cross

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 pivot to R_bad



Partitioning: In place (Hoare's)

Swap pivot to the front (position 1)

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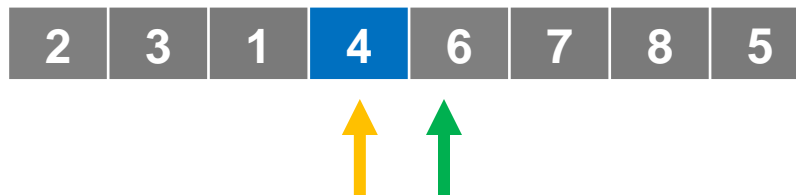
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move L_bad right until we find a “bad” element, i.e. $>$ pivot

move R_bad left until we find a “bad” element, i.e. $<$ pivot

swap these elements

swap pivot to R_bad



Partitioning: In place (Hoare's)

Swap pivot to the front (position 1)

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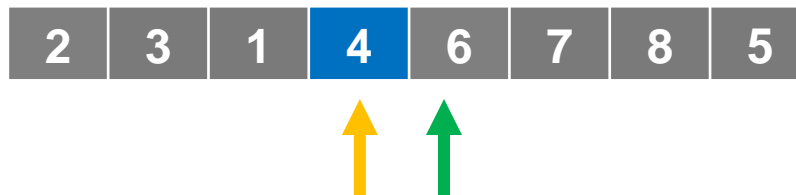
Repeat until L_bad and R_bad cross

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 pivot to R_bad



4 is now in sorted
position!

Partitioning: In place (Hoare's)

Swap pivot to the front (position 1)

L_bad = 2, R_bad = N

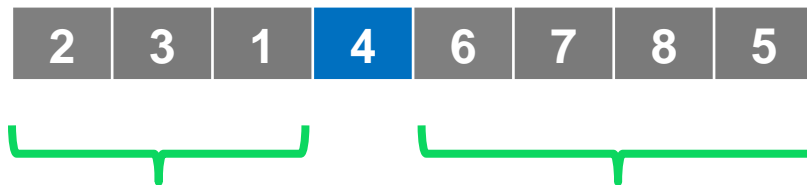
Repeat until L_bad and R_bad cross

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 pivot to R_bad



Repeat LEFT and RIGHT

Questions?

Quicksort

In-place Partitioning (Hoare's)

- Invariant?

Quicksort

In-place Partitioning (Hoare's)

- Invariant?
 - L_bad?
 - R_bad?

- Invariant?
 - L_bad? Everything to left of L_bad is less/ same than pivot
 - R_bad? Everything to right of R_bad is great than pivot

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- Invariant?
 - L_bad? Everything to left of L_bad is less/ same than pivot
 - R_bad? Everything to right of R_bad is great than pivot
 - Between? Not processed yet...
 - What about the pivot? Think about it...

Questions?

- 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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 - **The final swapping of the pivot from 1st position to R_bad would mess up the stability**

Quicksort

In-place Partitioning (Hoare's)

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



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 - **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?

Quicksort

In-place Partitioning (Hoare's)

- Code it out and see...

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 - There is another special edge case that cause this algorithm to fail...

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 - Unless you add in a special check =)

- 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 =(

choose the pivot as either biggest or smallest

Questions?

Quicksort

In-place Partitioning (Lomuto's)

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

Quicksort

In-place Partitioning (Lomuto's)

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

Quicksort

In-place Partitioning (Lomuto's)

- This is the one you are familiar with
 - From FIT1008
- In place
- Swap each element multiple times

- This is the one you are familiar with
 - From FIT1008
- In place
- Swap each element multiple times
- ... and still unstable

Hoare's would not swap

- This is the one you are familiar with
 - From FIT1008
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 - Worse than Hoare's
- ... and still unstable

- 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?

- So you now learnt all 3
 - Out-of-place
 - Hoare's
 - Lomuto's

- So you now learnt all 3
 - Out-of-place
 - Hoare's
 - Lomuto's

- And the entire partitioning gave us an idea to improve it more...
 - Due to the stability concern...

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Quicksort

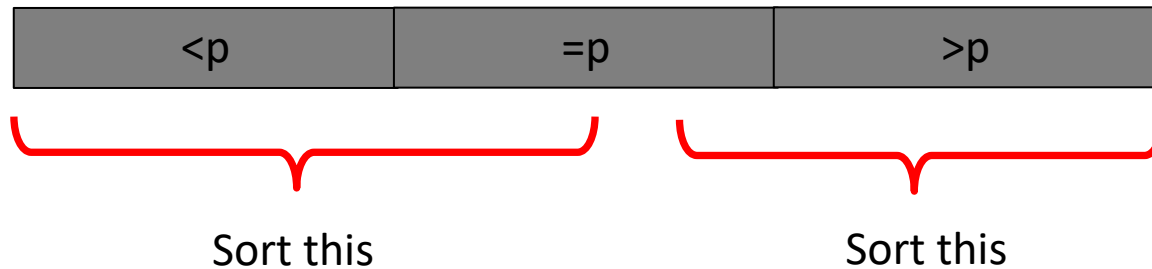
Partitioning...

- The stability issue however gives us an idea...

Quicksort

Partitioning...

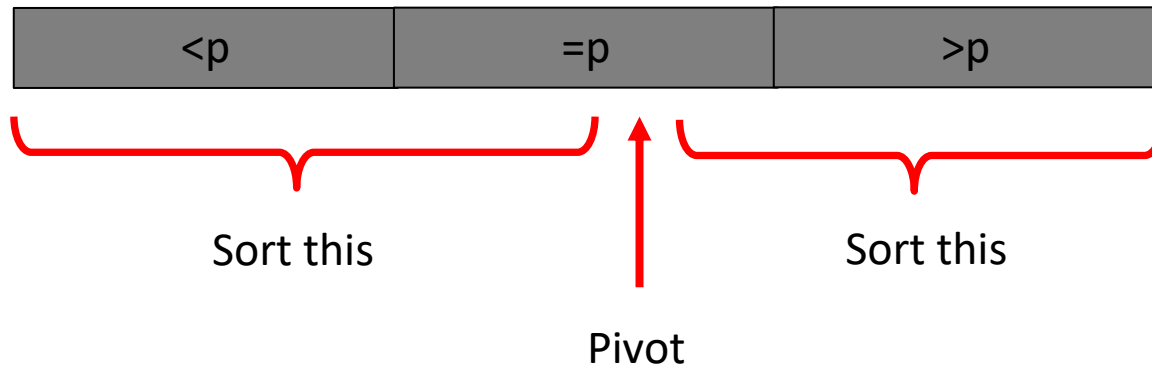
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Quicksort

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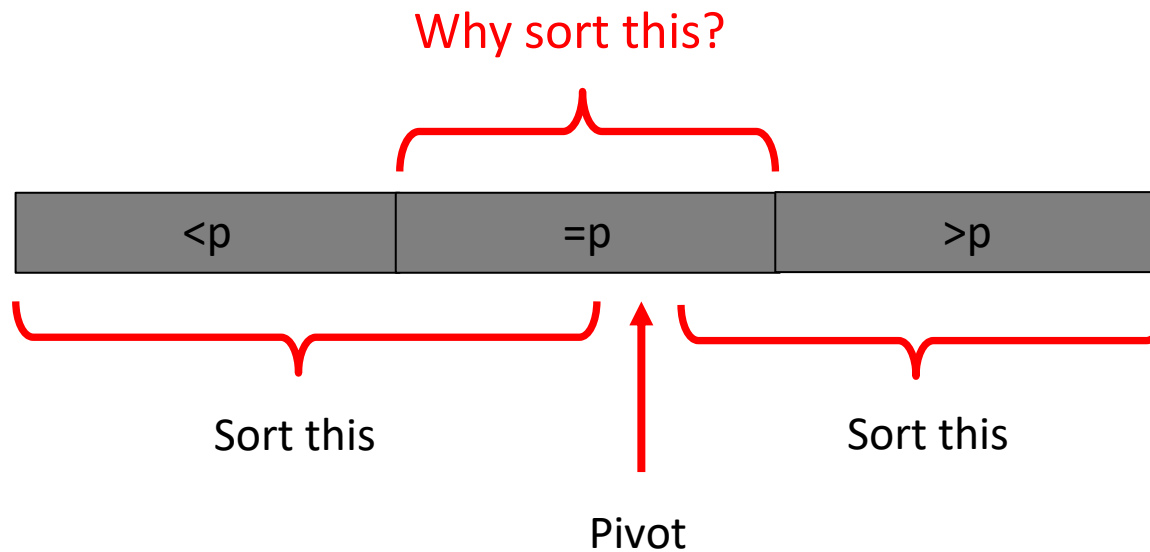
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Quicksort

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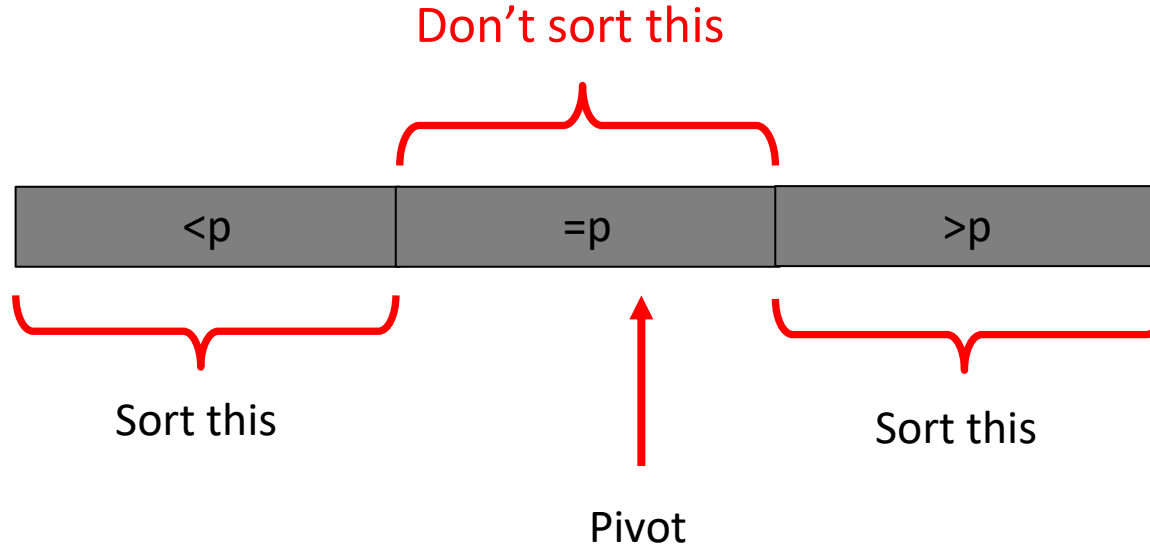
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Quicksort

Partitioning...

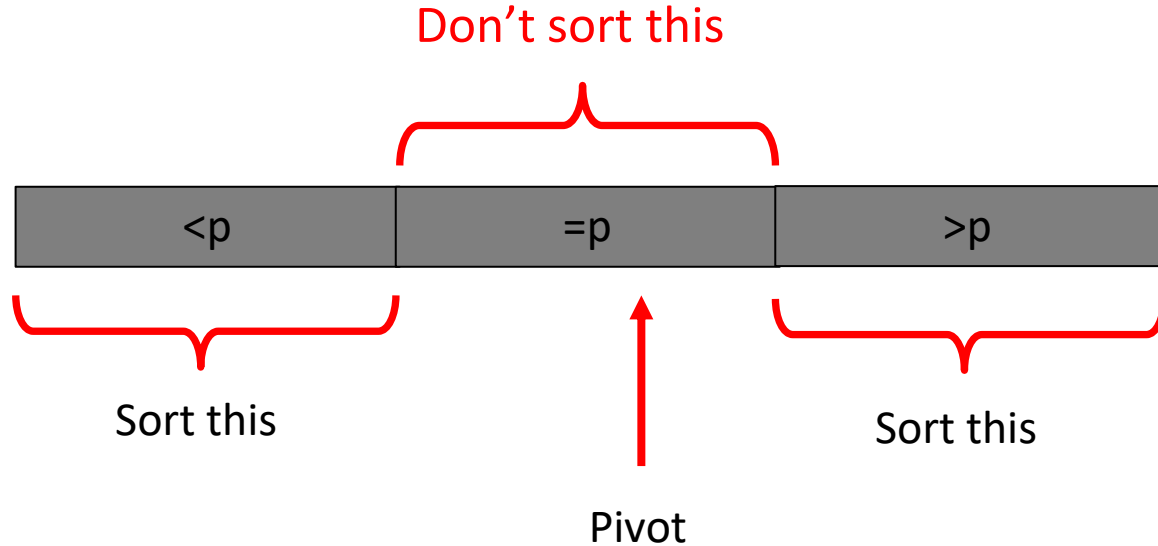
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Quicksort

Partitioning...

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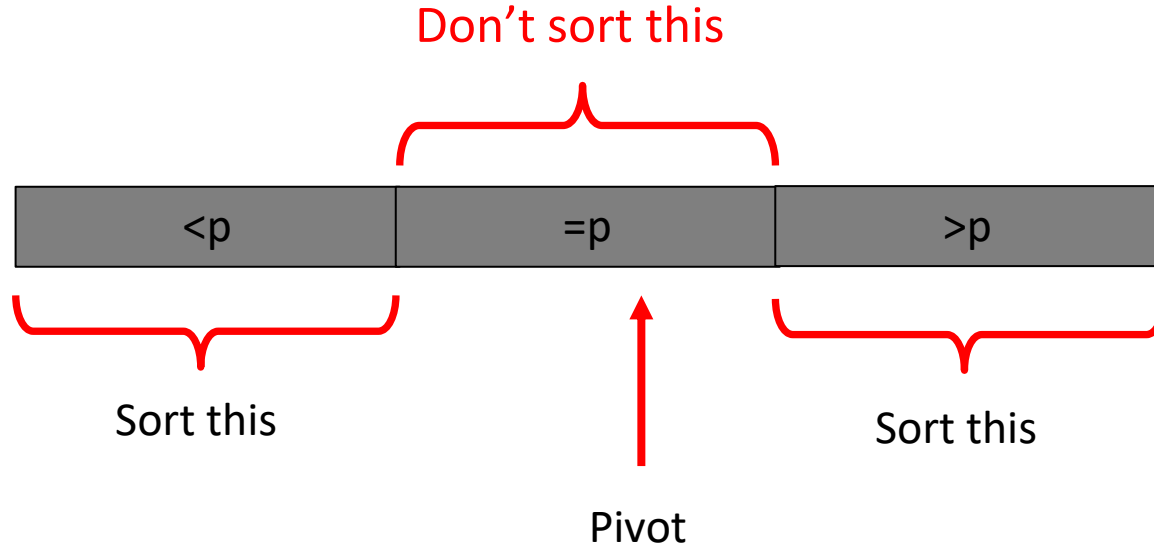


Quicksort

Partitioning...



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- This lead us to the Dutch national flag problem

Quicksort

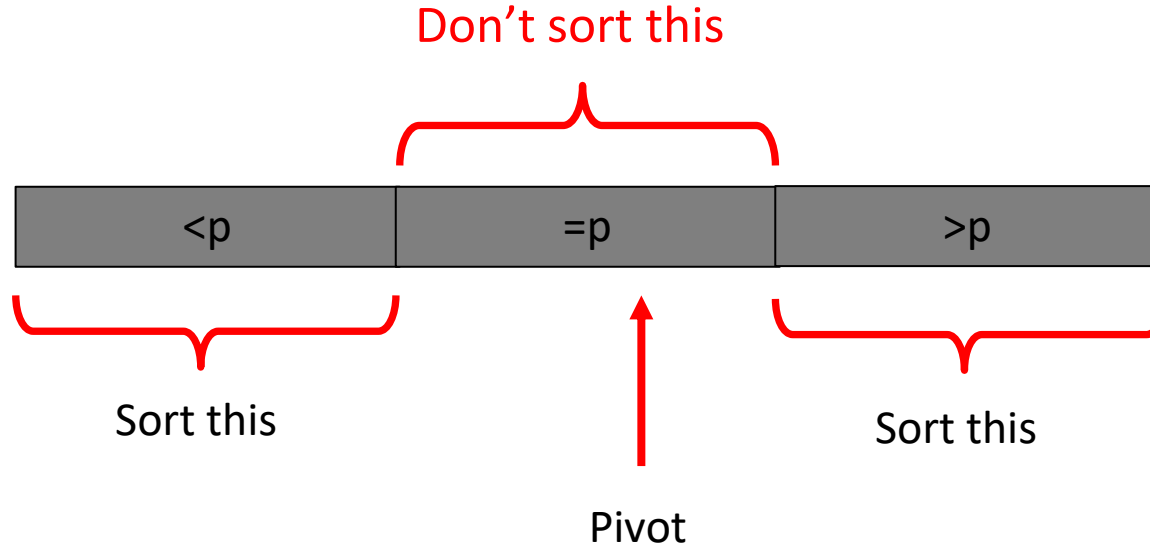
Partitioning...

< p

= p

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- The stability issue however gives us an idea...



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Quicksort

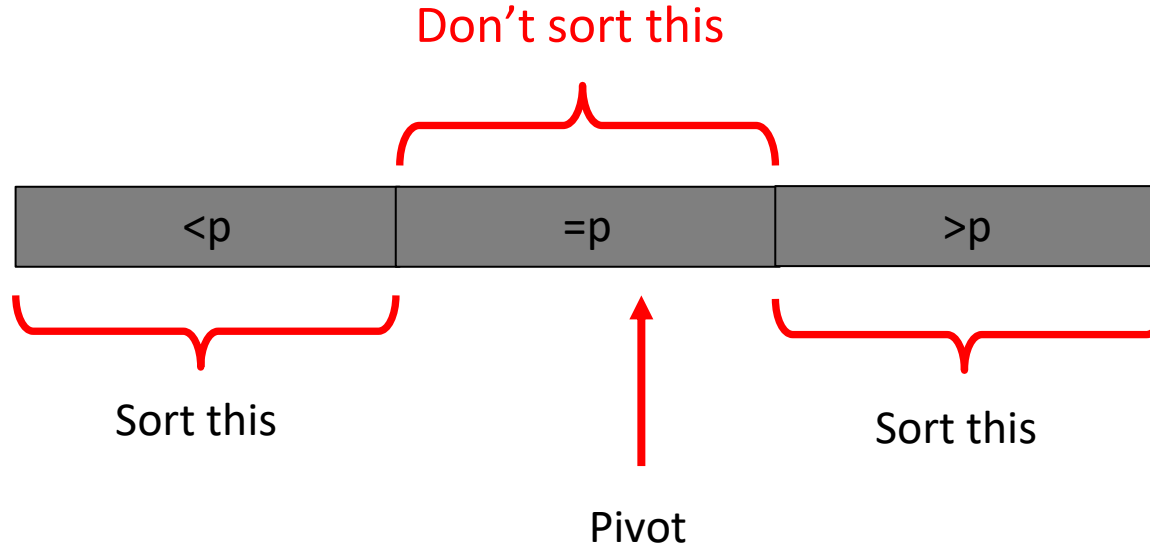
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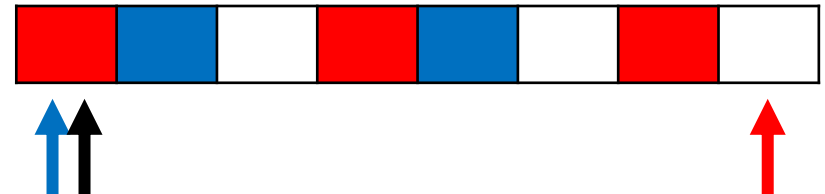
- This lead us to the Dutch national flag problem
 - Let us look at Nathan's illustration

Dutch National Flag Algorithm

boundary1=1,

j=1

boundary2 = n



Dutch National Flag Algorithm

boundary1=1,

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boundary2 = n

While j <= boundary2

if array[j] is blue

swap array[boundary1], array[j]

boundary1 += 1

j += 1

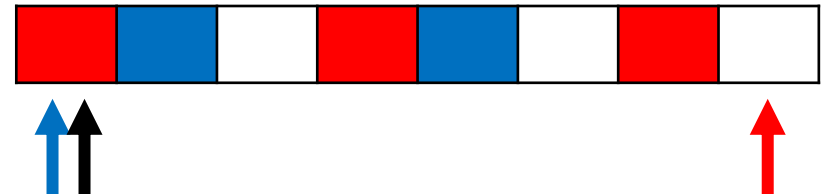
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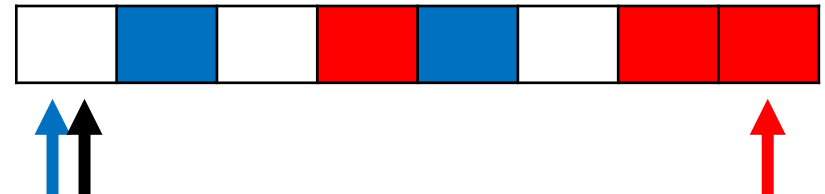
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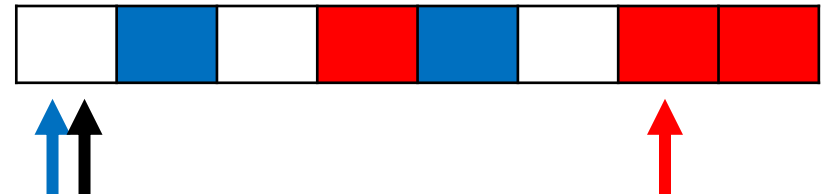
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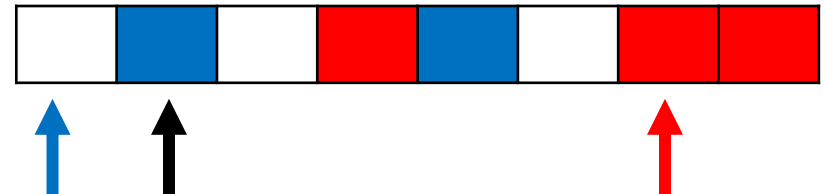
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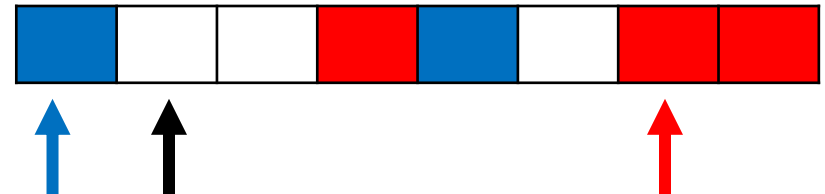
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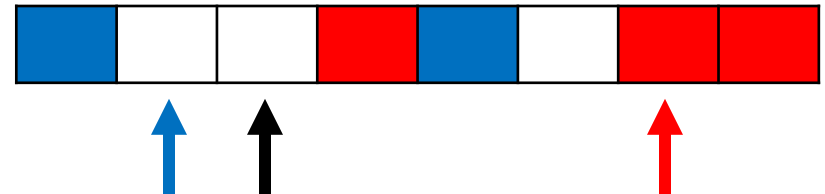
elif array[j] is red

swap array[j], array[boundary2]

boundary2 -= 1

else array[j] and blue_ boundary = white = +=1

j += 1



Dutch National Flag Algorithm

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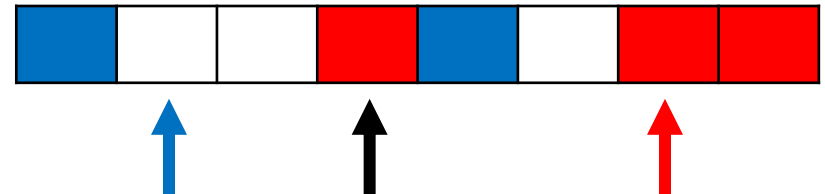
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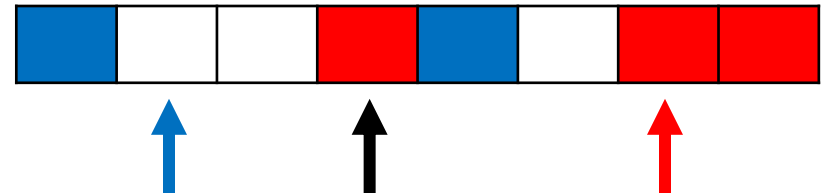
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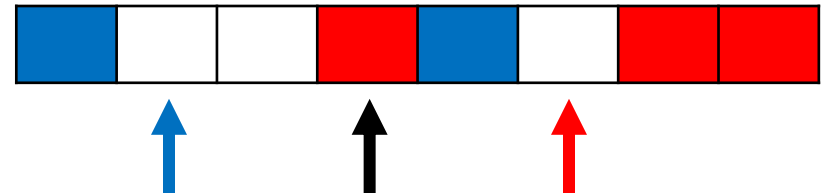
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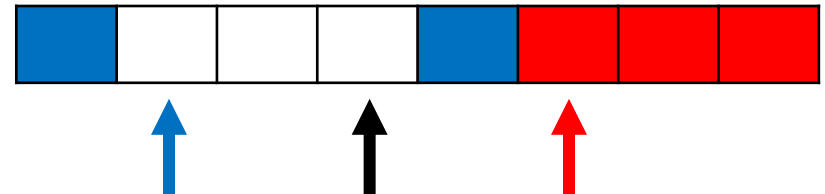
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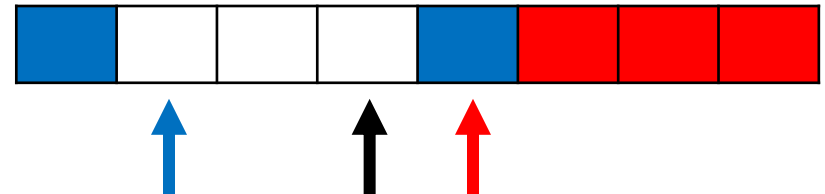
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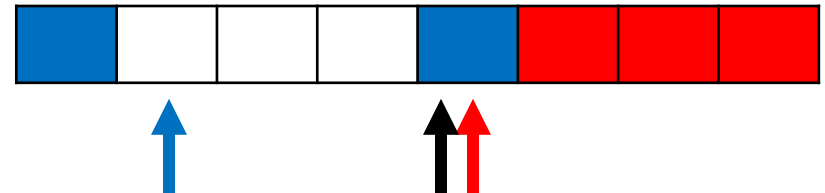
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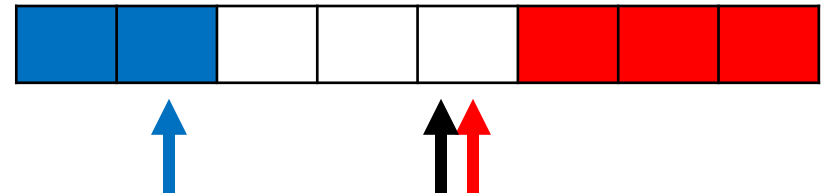
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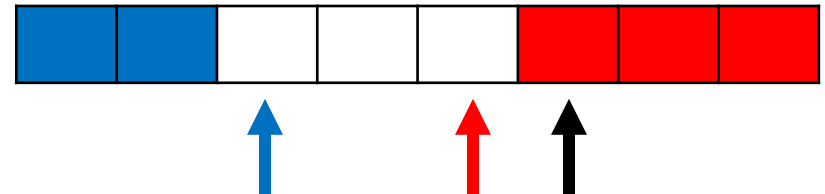
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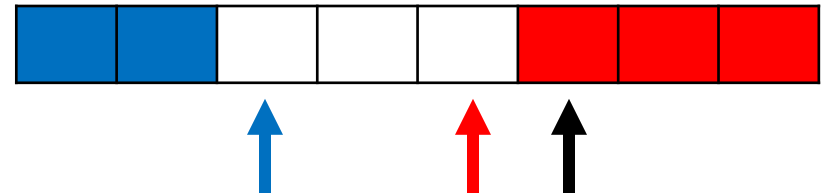
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Return boundary1, boundary2



Dutch National Flag Algorithm

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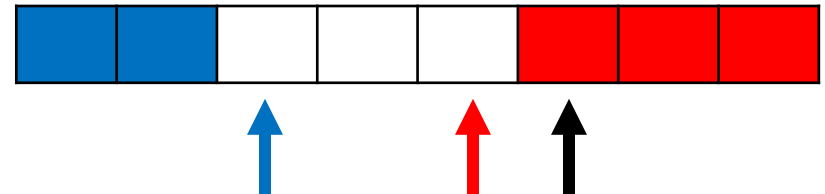
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Return boundary1, boundary2



Now quicksort the red and blue parts

Questions?

- 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 $j > \text{boundary2}$

- 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 $j > \text{boundary2}$

- 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?

Quicksort

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

Partitioning...

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 - Left partition and right partition is smaller now
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Quicksort

Partitioning...

- Minimize swaps
 - We saw this with Hoare's
- Minimize work in recursive sort
 - We saw this with Dutch national flag
 - Left partition and right partition is smaller now
- Be in-place
 - Save memory

Quicksort

Partitioning...

- Minimize swaps
 - We saw this with Hoare's
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 - Left partition and right partition is smaller now
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 - Save memory
- Stable?

Quicksort

Partitioning...

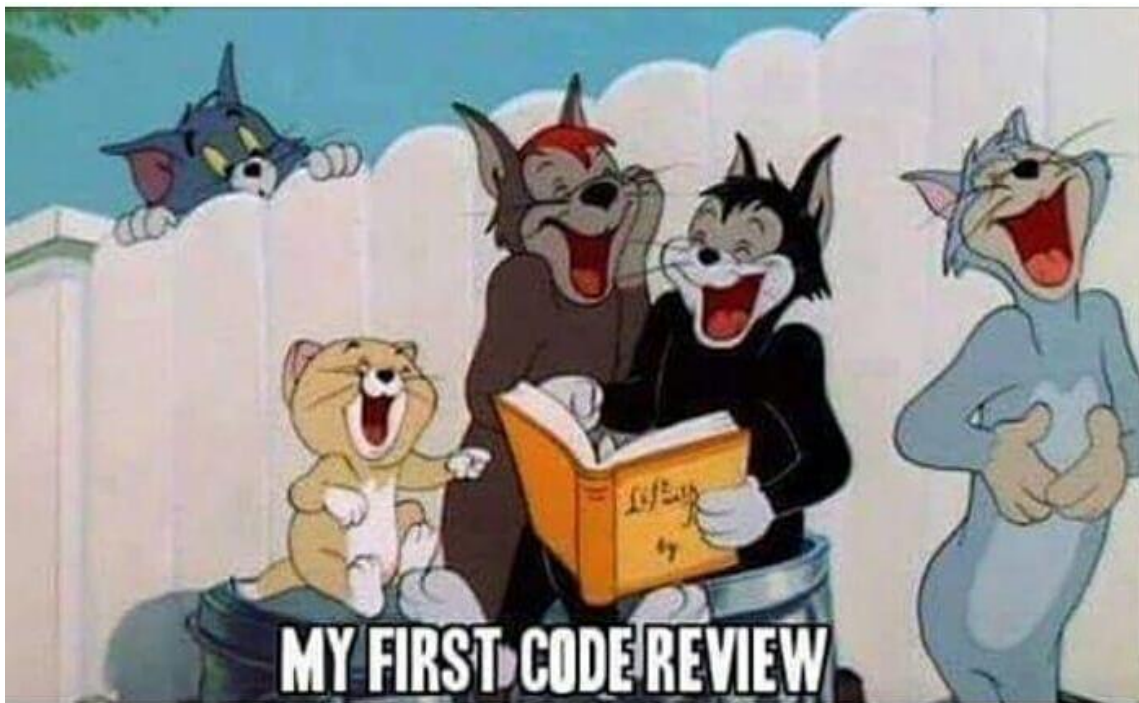
- Minimize swaps
 - We saw this with Hoare's
- Minimize work in recursive sort
 - We saw this with Dutch national flag
 - Left partition and right partition is smaller now
- Be in-place
 - Save memory
- Stable?
 - We discuss more in the tutorials...



Quicksort

Partitioning...

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



Questions?

Quicksort

Complexity Analysis

- Time complexity

Quicksort

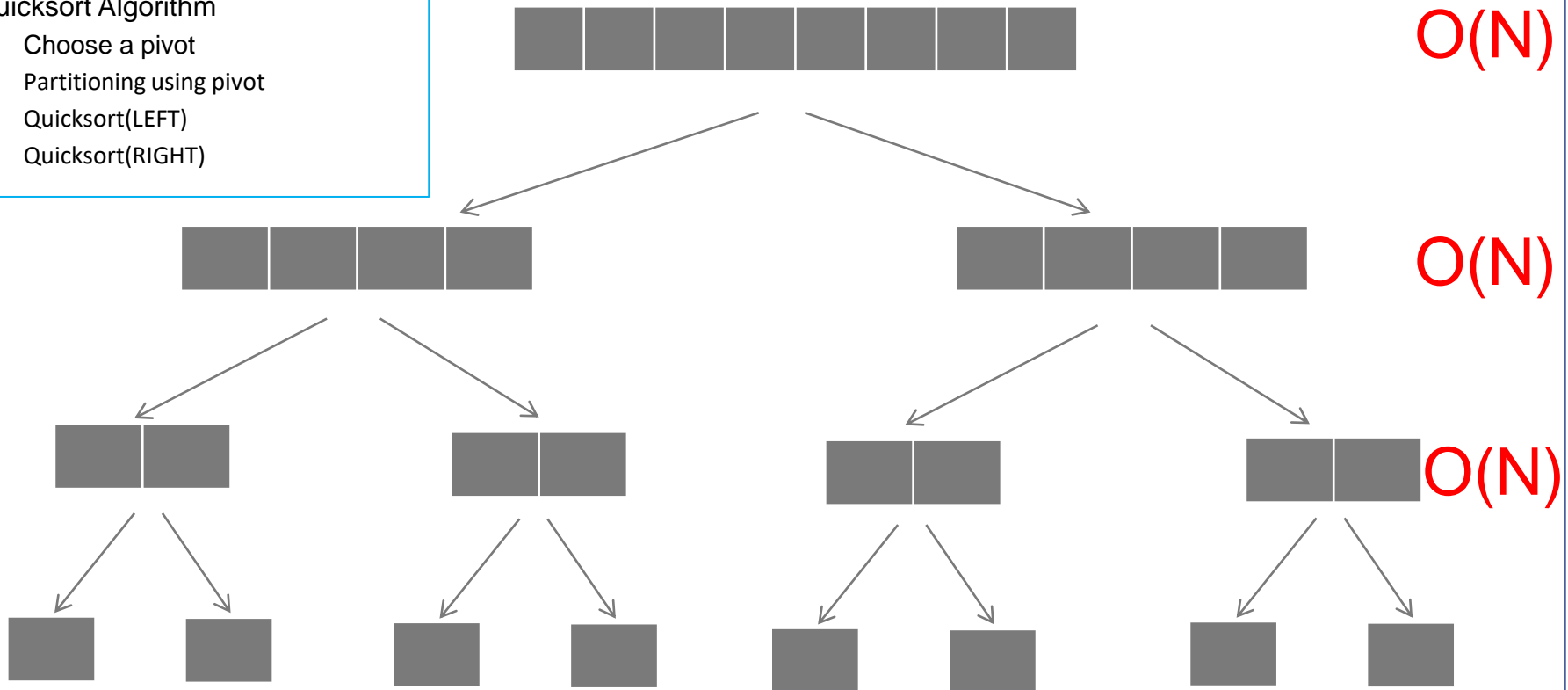
Complexity Analysis

- Time complexity
 - Best
 - Worst

Best-case time complexity

Quicksort Algorithm

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



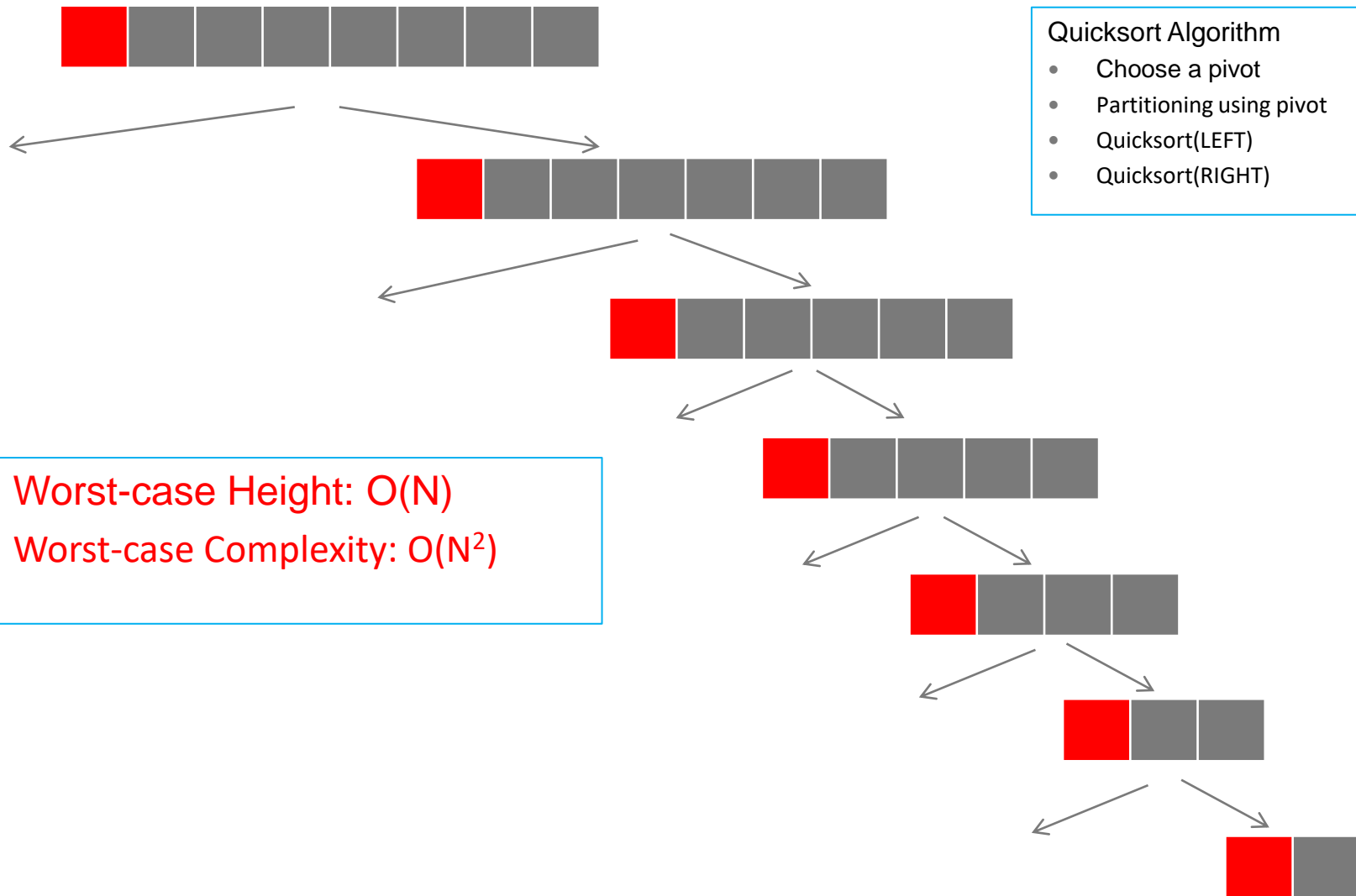
Best-case Height: $O(\log N)$

Best-case complexity: $O(N \log N)$

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

Recursion depth is at least $O(\log N)$

Worst-case Time Complexity



Quicksort

Complexity Analysis

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

Quicksort

Complexity Analysis

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

Complexity Analysis

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 - Best
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 - $O(N \log N)$
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 - $O(N^2)$
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Questions?

Quicksort

Complexity Analysis

- Or we can use math
 - Like in tutorial

Quicksort

Complexity Analysis

- 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:

$$O(N^2) \quad \text{either far left or far right}$$



Questions?

Quicksort

Complexity Analysis

- Time complexity
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 - We all know this from so many discussions in FIT1008
 - Something new is average complexity...
 - This is something I usually prefer to explain by hand in class, let me try here...

Quicksort

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 - Why?

Quicksort

Complexity Analysis

- Time complexity
 - Best
 - When pivot split left-right evenly
 - $O(N \log N)$
 - Worst
 - 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...
 - This is something I usually prefer to explain by hand in class, let me try here...
 - quicksort does not include pivot
 - better than merge sort less work on every recursion
 - on average complexity
 - Why?

Questions?

Quicksort

Complexity Analysis

- Consider a list with N elements

Quicksort

Complexity Analysis

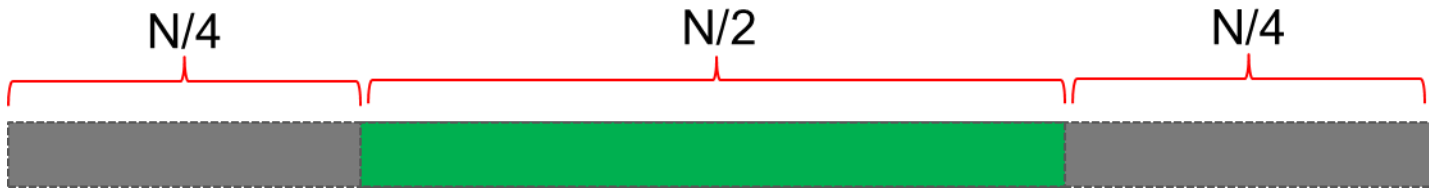
- Consider a list with N elements
 - And then we partition it



Quicksort

Complexity Analysis

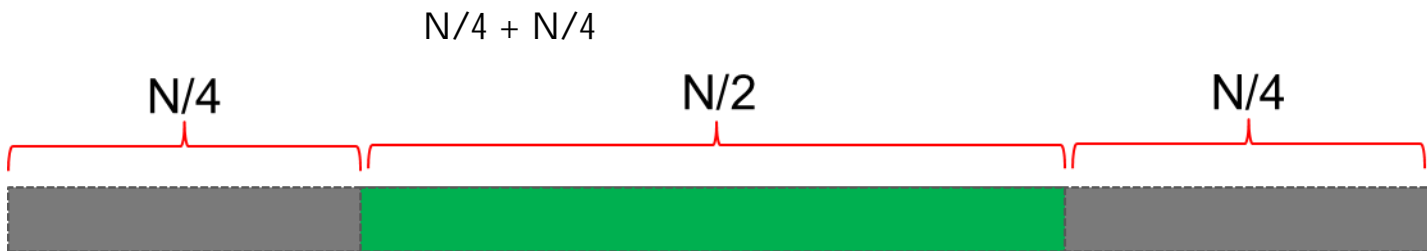
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Quicksort

Complexity Analysis

- Consider a list with N elements
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- What is the probability we would land on the green area?

Quicksort

Complexity Analysis

- Consider a list with N elements
 - And then we partition it



- What is the probability we would land on the green area?
 - So 50% probability

Quicksort

Complexity Analysis

- Consider a list with N elements
 - And then we partition it

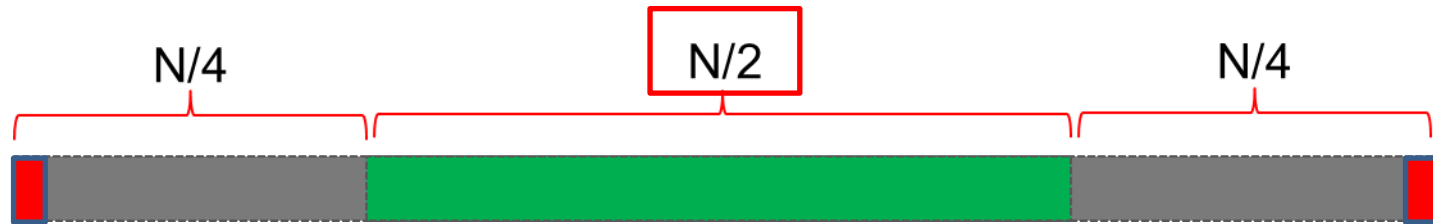


- What is the probability we would land on the green area?
 - So 50% probability
- Worst case in grey area?

Quicksort

Complexity Analysis

- Consider a list with N elements
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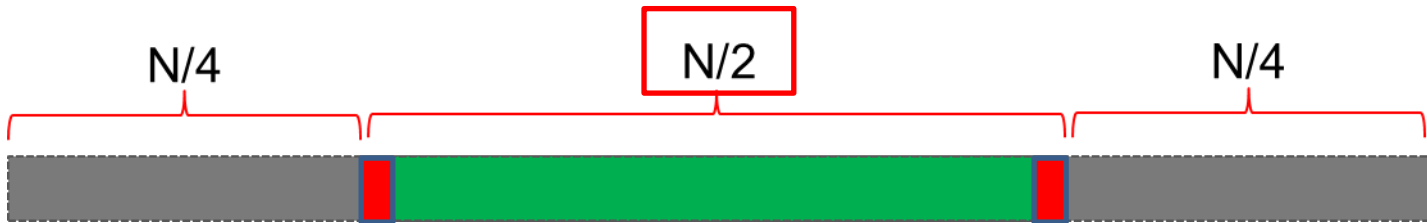


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Quicksort

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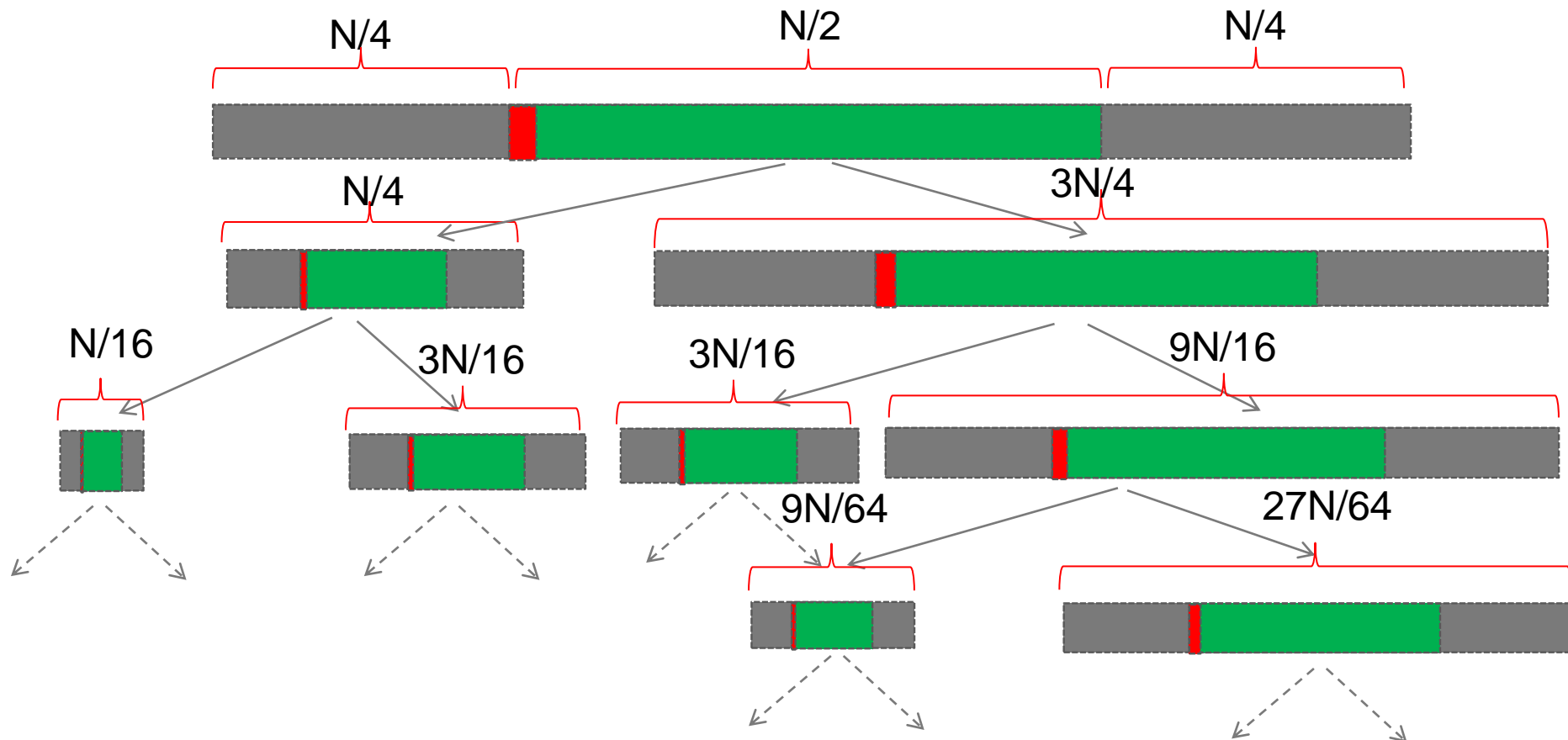
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- If we always hit the green area, we will get a maximum recursion height of h ... So what is the upper bound for the height if we land on green 50%? $2h$ $\log_2 N = h$ if pivot in the middle
upper bound = $2h$ (if pivot fall at the end) worse case

- So we calculate what is h

Quicksort

Complexity Analysis

- Let us just do the normal drawing



Quicksort

Complexity Analysis

- Let us just do the normal drawing
 - From your recursive knowledge, $T(N) \rightarrow T(3N/4)$

Quicksort

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Quicksort

Complexity Analysis

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 - From your recursive knowledge, $T(N) \rightarrow T(3N/4)$
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 - Thus... $N(3/4)^h = 1$

Quicksort

Complexity Analysis

- Let us just do the normal drawing higher complexity partition one
 - From your recursive knowledge, $T(N) \rightarrow T(3N/4)$
 - Reach base case when size is 1, thus base when $T(1)$
 - Thus... $N(3/4)^h = 1$
 - Which gives us $(3/4)^h N = 1 \rightarrow N = (4/3)^h \rightarrow h = \log_{4/3} N$

Quicksort

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Quicksort

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 - Which gives us $(3/4)^h N = 1 \rightarrow N = (4/3)^h \rightarrow h = \log_{4/3} N$
 - 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 $2h$

Quicksort

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 - Our maximum depth for average case is $2h$
 - Which give us $2 \log_{4/3} N$

Quicksort

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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: $\log_a N = \frac{\log_b N}{\log_b a}$ constant

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

Questions?

Quicksort

Complexity Analysis

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

Quicksort

Complexity Analysis

- Can be done with math as well
 - 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)
...	...
<div> <div>Quicksort Algorithm</div> <ul style="list-style-type: none"> Choose a pivot Partitioning using pivot Quicksort(LEFT) Quicksort(RIGHT) </div>	
	T(N-3)
	T(N-2)
	T(N-1)

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

Average-case complexity using recurrence (NOT EXAMINABLE)

Recurrence relation:

$$T(1) = b$$

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

Multiplying N on both sides

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

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

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

(A) - (B)

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

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

Simplify

Divide both sides by N

Average-case complexity using recurrence (NOT EXAMINABLE)

Recurrence relation:

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

Let's solve it:

$$T(N-1) = 2 + \frac{N}{N-1} T(N-2) \leftarrow \text{Cost for } T(N-1)$$

Replace $T(N-1)$ in (A)

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

$$T(N-2) = 2 + \frac{N-1}{N-2} T(N-3) \leftarrow \text{Cost for } T(N-2)$$

Replace $T(N-2)$ in (B)

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

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

See the pattern for k ?

Average-case complexity using recurrence

(NOT EXAMINABLE)

Recurrence relation:

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

Let's solve it:

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

$$N-k=1 \rightarrow k=N-1$$

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

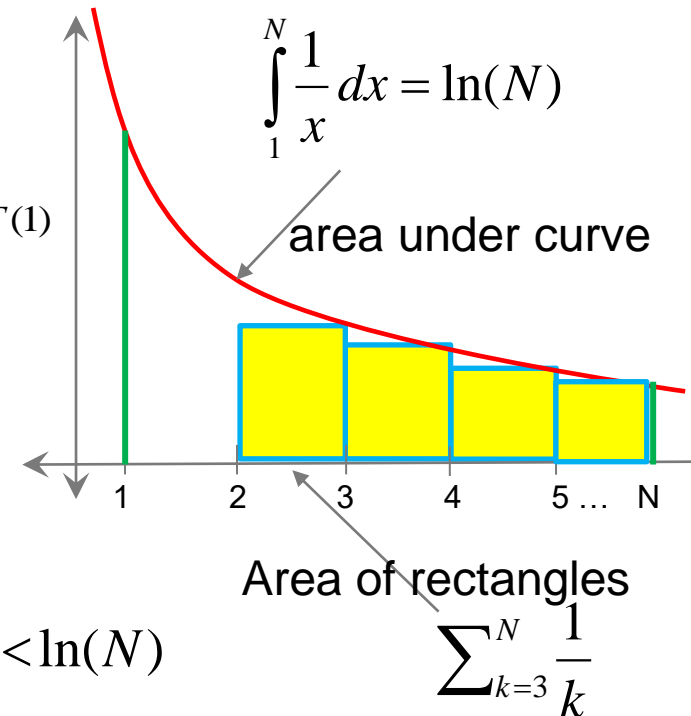
Simplify

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

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

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

$$T(N) = O(N \log N)$$



Questions?

Quick Sort

Summary

- Good sorting algorithm
 - Using divide and conquer

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- And we looked at the complexity
 - Best case
 - Worst case
 - Average case

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 - Unlike merge sort
- And we looked at the complexity
 - Best case
 - Worst case
 - Average case
 - Everything depends on **pivot**! Next lecture on how to select **pivot**

Questions?

Thank You