

CS473 - Algorithms I



Lecture 5 Quicksort

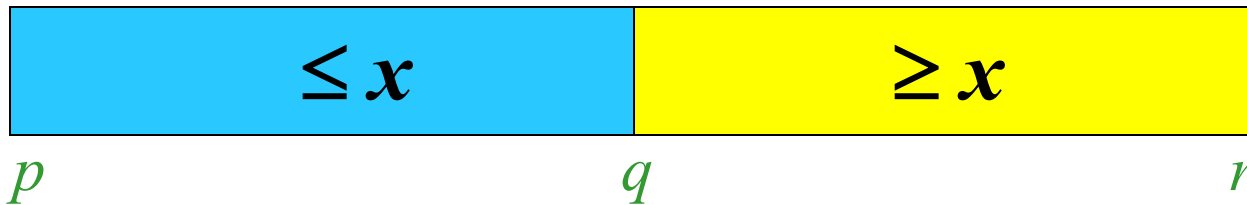
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Quicksort

- One of the most-used algorithms in practice
- Proposed by C.A.R. Hoare in 1962.
- Divide-and-conquer algorithm
- In-place algorithm
 - ▣ The additional space needed is $O(1)$
 - ▣ The sorted array is returned in the input array
 - ▣ *Reminder: Insertion-sort is also an in-place algorithm, but Merge-Sort is not in-place.*
- Very practical

Quicksort

1. **Divide:** Partition the array into 2 subarrays such that elements in the lower part \leq elements in the higher part



2. **Conquer:** Recursively sort 2 subarrays
 3. **Combine:** Trivial (because in-place)
- Key: Linear-time ($\Theta(n)$) partitioning algorithm

Divide: Partition the array around a pivot element

1. Choose a **pivot** element x
2. Rearrange the array such that:
Left subarray: All elements $\leq x$
Right subarray: All elements $\geq x$

Input:

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

 e.g. $x = 5$

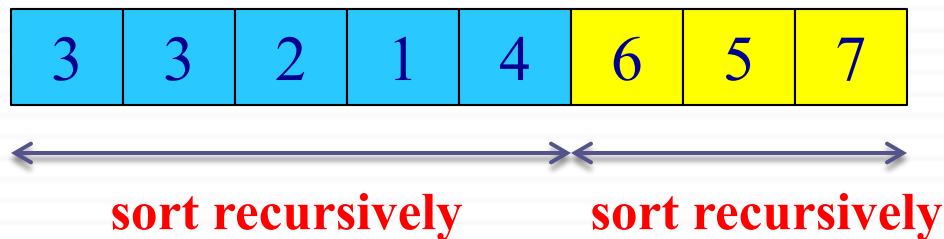
After partitioning:

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

 $\xleftrightarrow{\leq 5}$ $\xleftrightarrow{\geq 5}$

Conquer: Recursively Sort the Subarrays

Note: Everything in the left subarray \leq everything in the right subarray



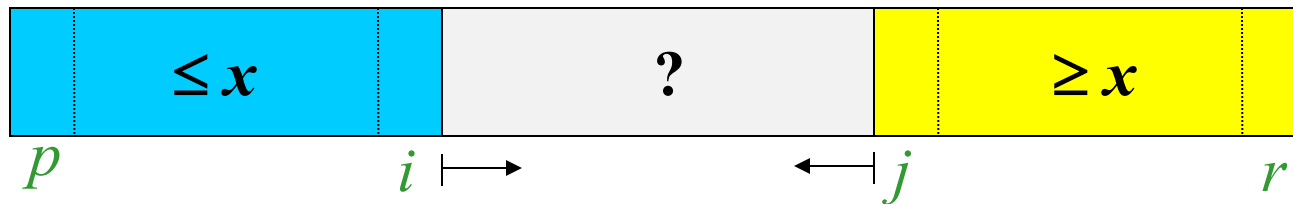
After conquer:

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

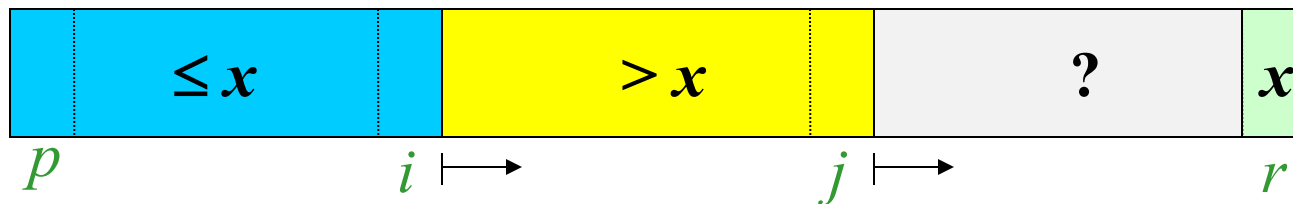
Note: Combine is trivial after conquer. Array already sorted.

Two partitioning algorithms

1. **Hoare's algorithm:** Partitions around the first element of subarray ($pivot = x = A[p]$)



2. **Lomuto's algorithm:** Partitions around the last element of subarray ($pivot = x = A[r]$)



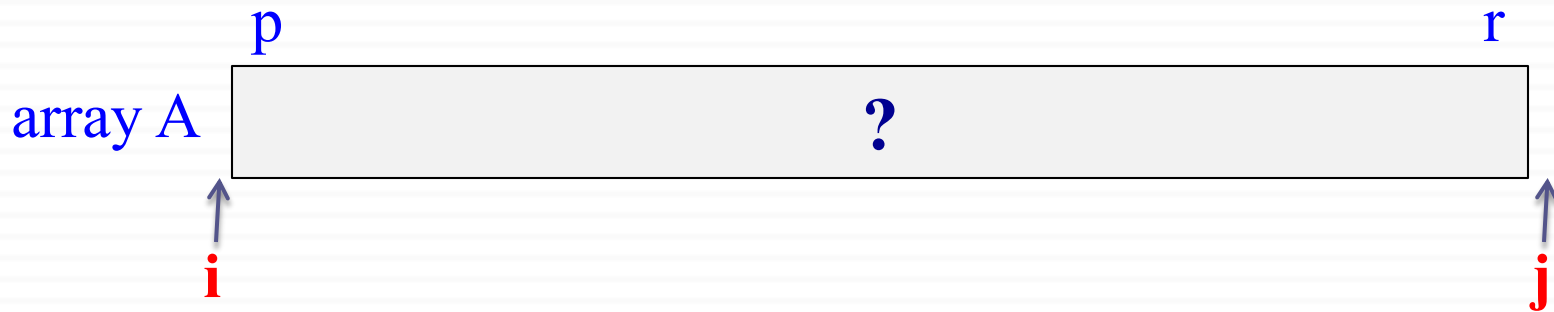
Hoare's Partitioning Algorithm

1. **Choose** a pivot element: $\text{pivot} = x = A[p]$
2. **Grow** two regions:
 - from **left to right**: $A[p..i]$
 - from **right to left**: $A[j..r]$such that:
 - every element in $A[p..i] \leq \text{pivot}$
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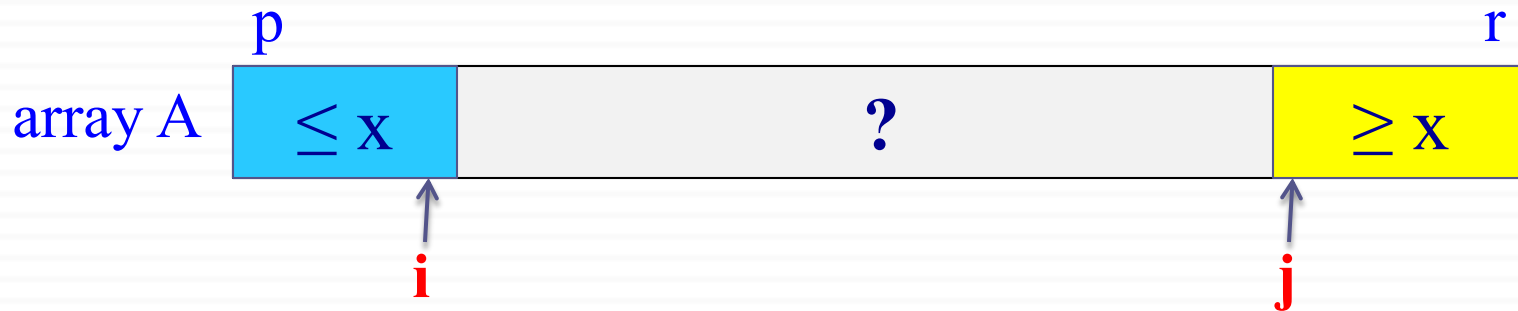
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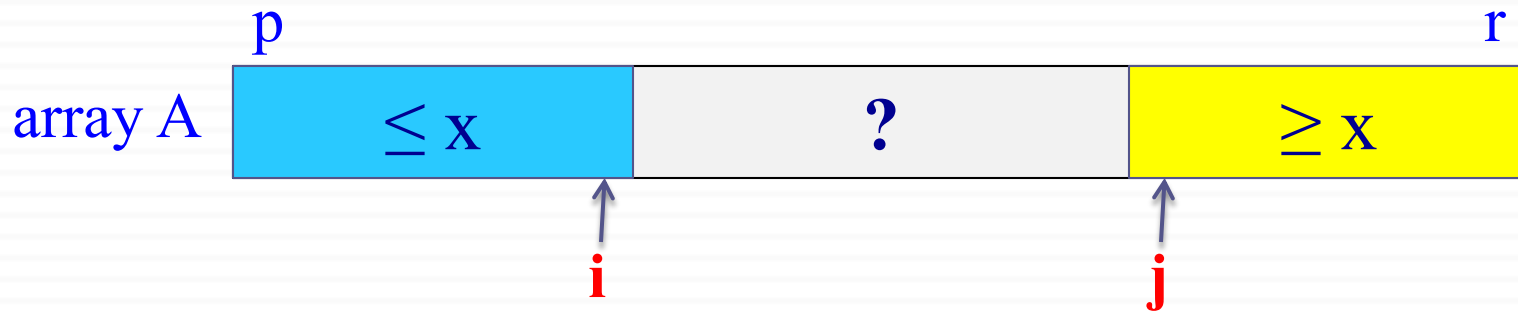
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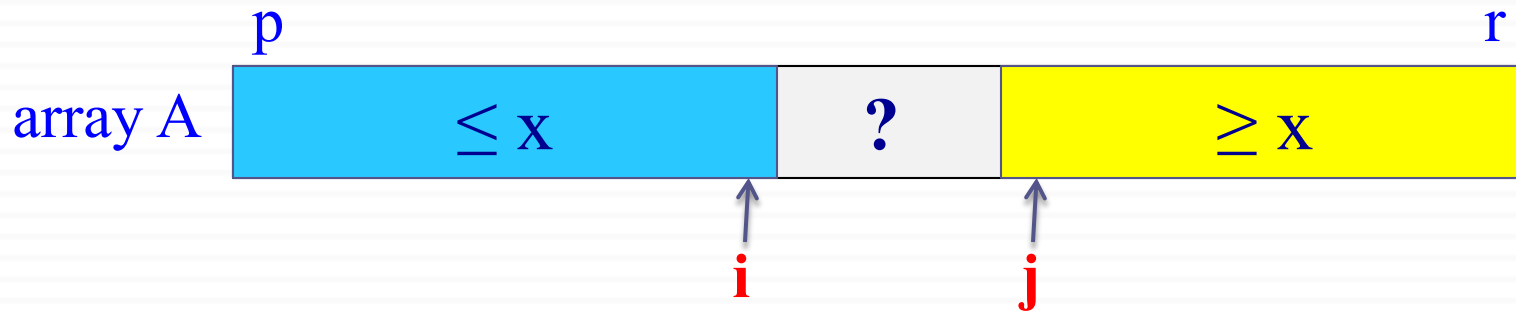
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Hoare's Partitioning Algorithm

H-PARTITION (A, p, r)

$pivot \leftarrow A[p]$

$i \leftarrow p - 1$

$j \leftarrow r + 1$

while true do

repeat $j \leftarrow j - 1$ **until** $A[j] \leq pivot$

repeat $i \leftarrow i + 1$ **until** $A[i] \geq pivot$

if $i < j$ **then** exchange $A[i] \leftrightarrow A[j]$

else return j



pivot = 5

Hoare's Partitioning Algorithm

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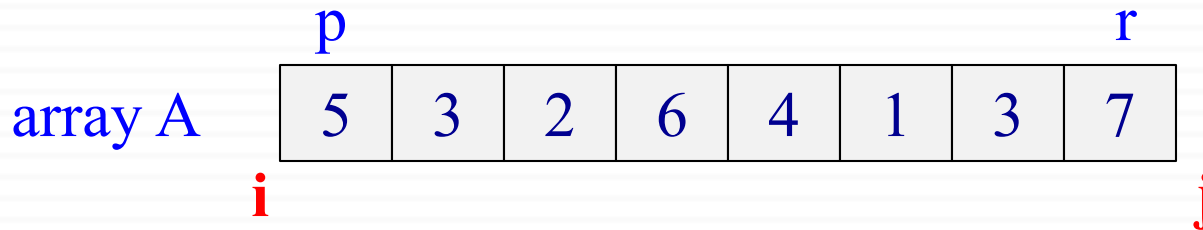
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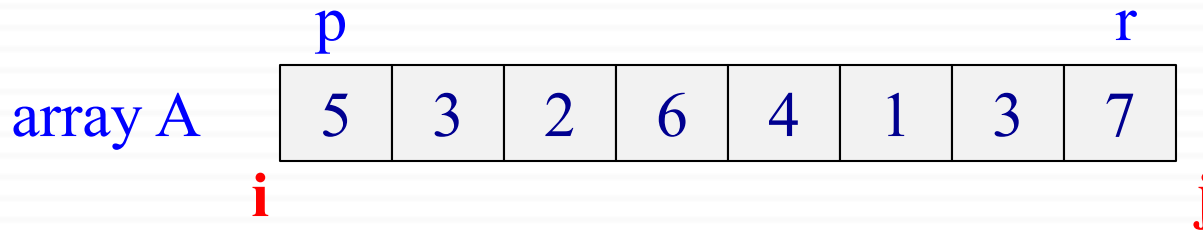
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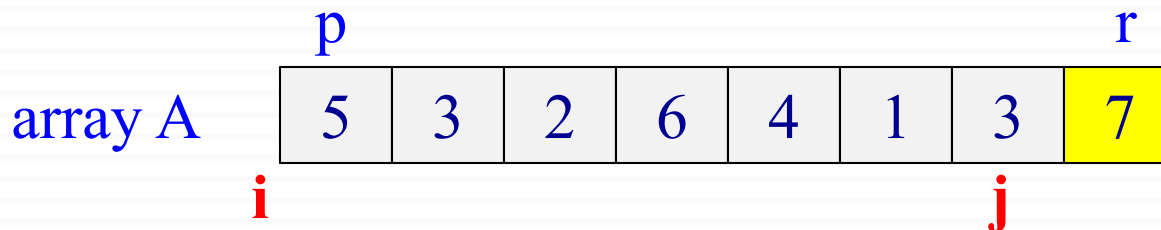
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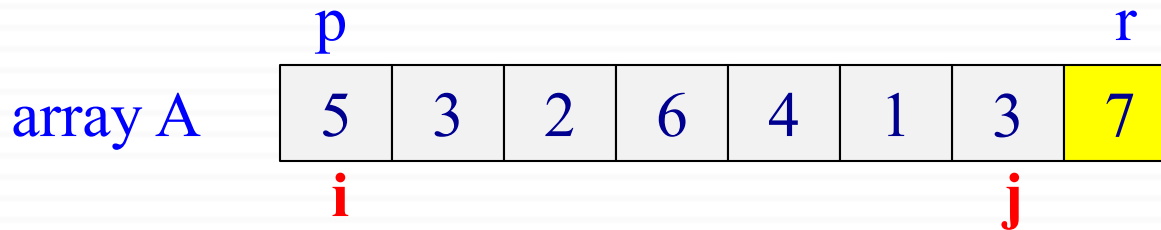
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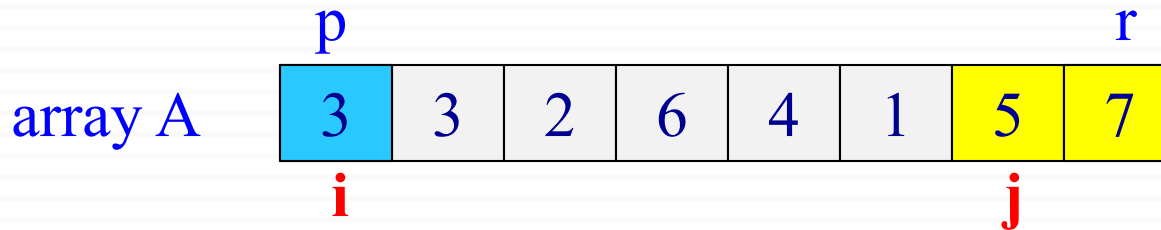
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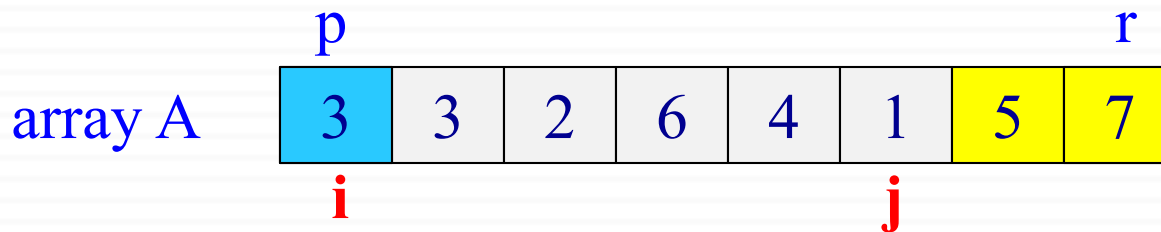
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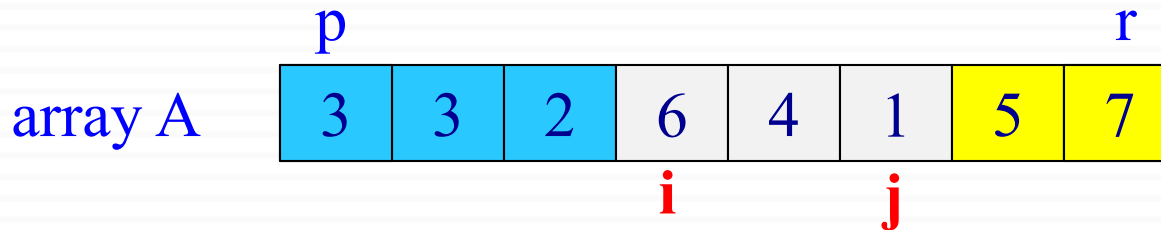
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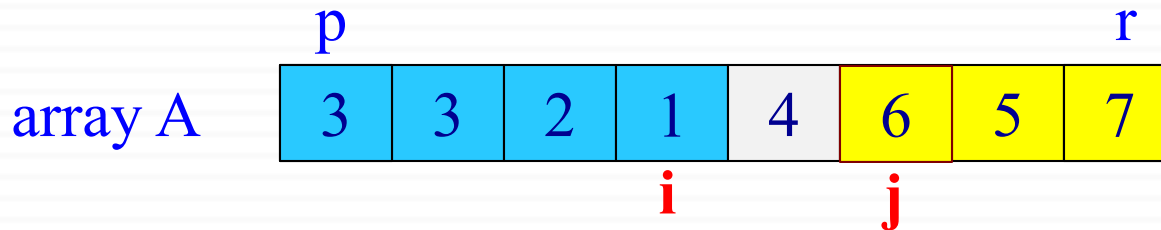
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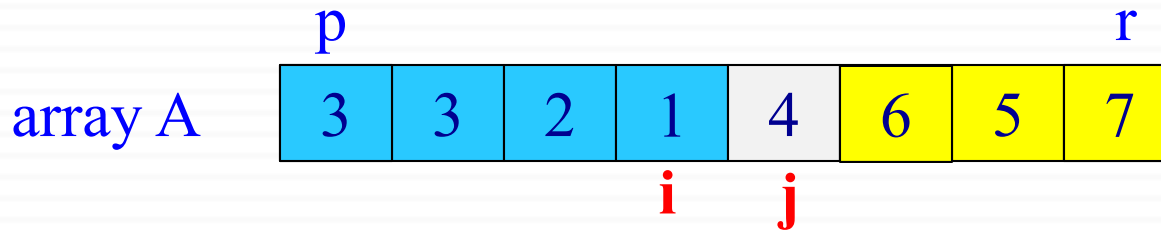
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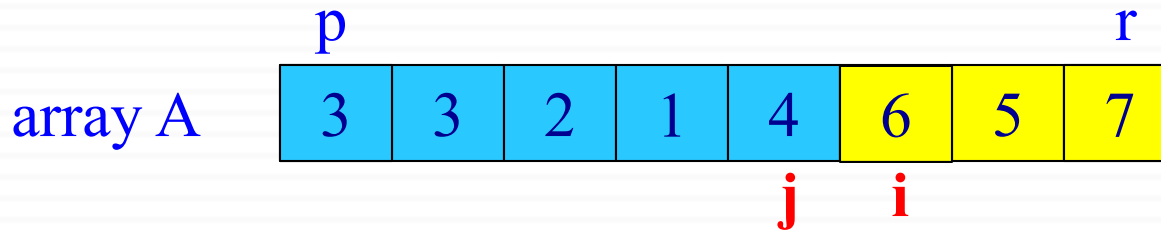
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Hoare's Partitioning Algorithm - Notes

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if $i < j$ **then** exchange $A[i] \leftrightarrow A[j]$

else return j

Elements are exchanged when

- $A[i]$ is **too large** to belong to the **left** region
- $A[j]$ is **too small** to belong to the **right** region

assuming that the inequality is strict

The two regions $A[p..i]$ and $A[j..r]$ grow until
 $A[i] \geq pivot \geq A[j]$

Hoare's Partitioning Algorithm

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What is the asymptotic runtime of Hoare's partitioning algorithm?

$\Theta(n)$

QUICKSORT (A, p, r)

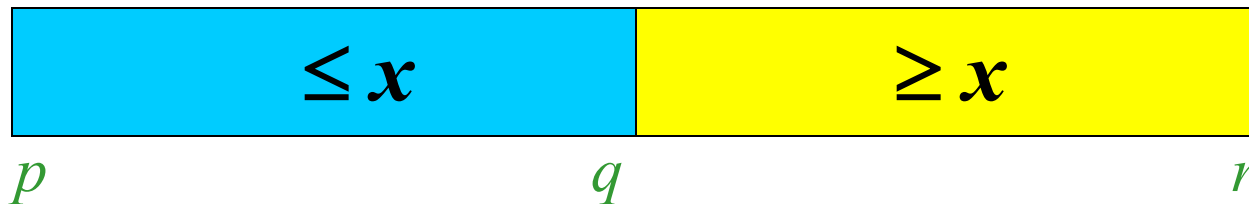
if $p < r$ then

$q \leftarrow \text{H-PARTITION}(A, p, r)$

QUICKSORT(A, p, q)

QUICKSORT($A, q + 1, r$)

Initial invocation: QUICKSORT($A, 1, n$)



Question

H-PARTITION (A, p, r)

$pivot \leftarrow A[p]$

$i \leftarrow p - 1$

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while true do

repeat $j \leftarrow j - 1$ **until** $A[j] \leq pivot$

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QUICKSORT (A, p, r)




if $p < r$ **then**

$q \leftarrow \text{H-PARTITION}(A, p, r)$

$\text{QUICKSORT}(A, p, q)$

$\text{QUICKSORT}(A, q + 1, r)$

Q: What happens if we select pivot to be $A[r]$ instead of $A[p]$ in **H-PARTITION**?

-  a) *QUICKSORT* will still work correctly.
-  b) *QUICKSORT* may return incorrect results for some inputs.
-  c) *QUICKSORT* may not terminate for some inputs.

Hoare's Partitioning Algorithm: Pivot Selection

H-PARTITION (A, p, r)

$pivot \leftarrow A[p]$

$i \leftarrow p - 1$

$j \leftarrow r + 1$

while true do

repeat $j \leftarrow j - 1$ **until** $A[j] \leq pivot$

repeat $i \leftarrow i + 1$ **until** $A[i] \geq pivot$

if $i < j$ **then** exchange $A[i] \leftrightarrow A[j]$

else return j

If $A[r]$ is chosen as the pivot:

Consider the example where $A[r]$ is the largest element in the array:

5	3	6	4	3	7
---	---	---	---	---	---

End of H-PARTITION: $i = j = r$

In QUICKSORT: $q = r$

So, recursive call to:

QUICKSORT ($A, p, q=r$)
→ infinite loop

QUICKSORT (A, p, r)

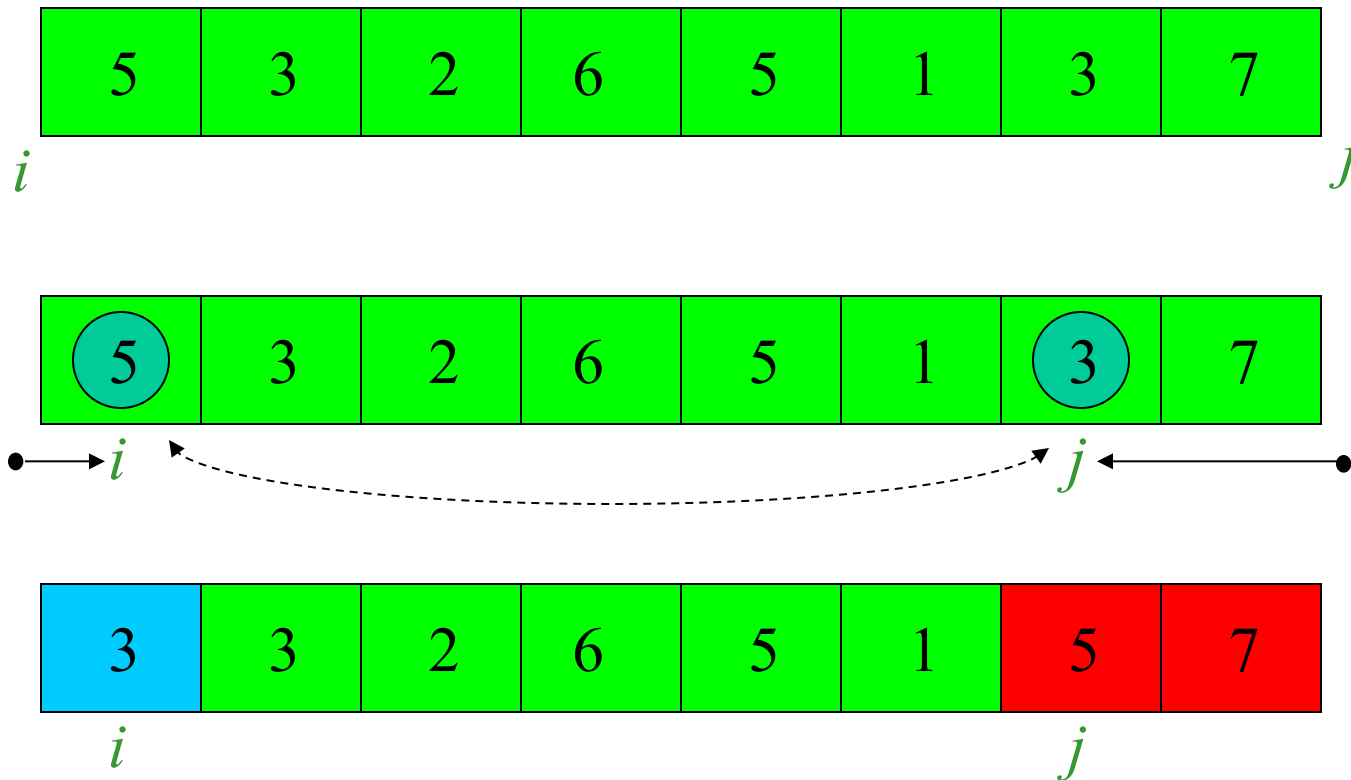
if $p < r$ **then**

$q \leftarrow$ H-PARTITION(A, p, r)

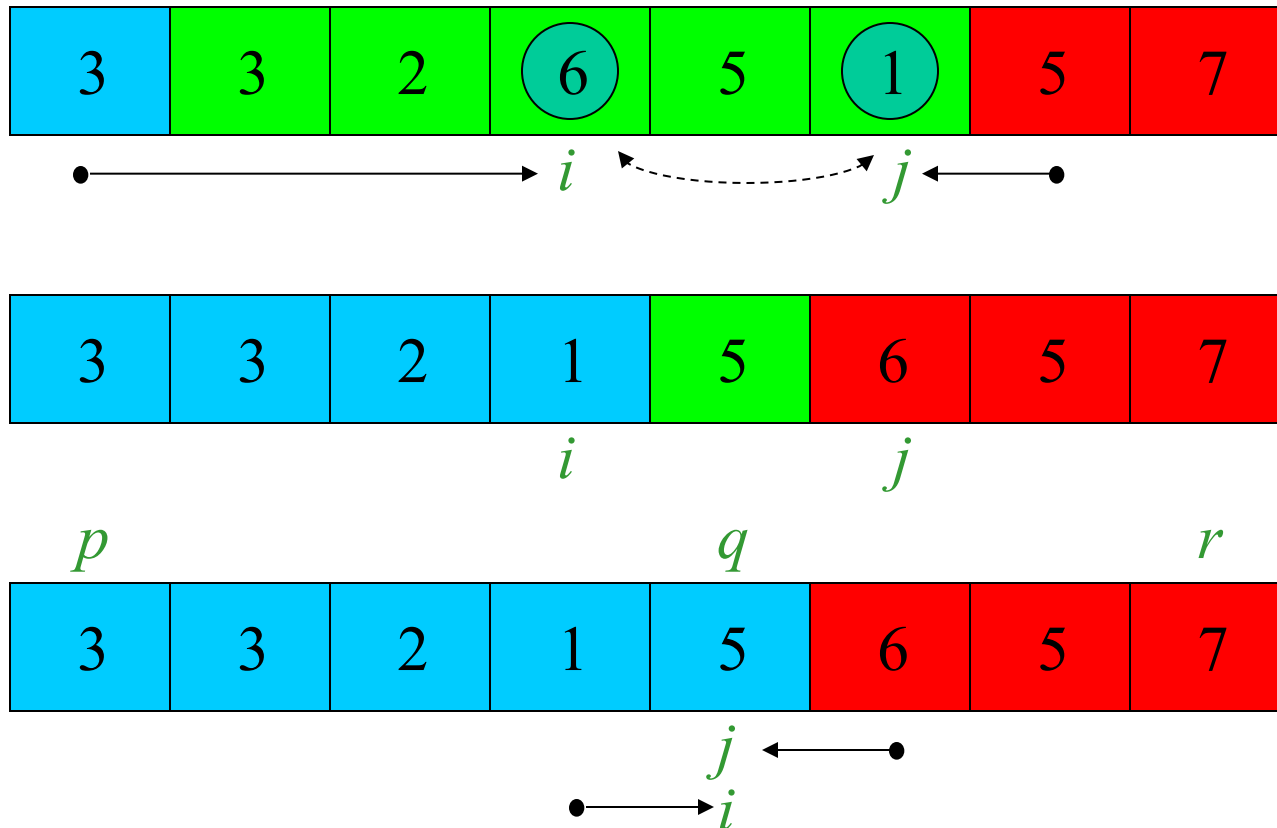
QUICKSORT(A, p, q)

QUICKSORT($A, q + 1, r$)

Hoare's Algorithm: Example 2 (pivot = 5)



Hoare's Algorithm: Example 2 (pivot = 5)

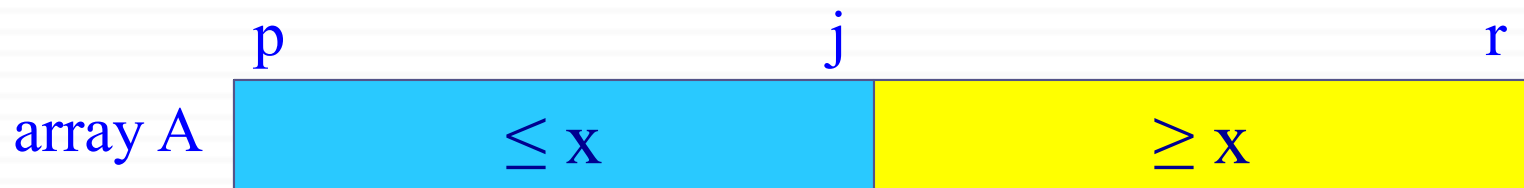


Termination: $i = j = 5$

Correctness of Hoare's Algorithm

We need to prove 3 claims to show correctness:

- a) Indices i & j never reference A outside the interval $A[p..r]$
- b) Split is always non-trivial; i.e., $j \neq r$ at termination
- c) Every element in $A[p..j] \leq$ every element in $A[j+1..r]$ at termination



Correctness of Hoare's Algorithm

Notations:

k : # of times the while-loop iterates until termination

i_m : the value of index i at the end of iteration m

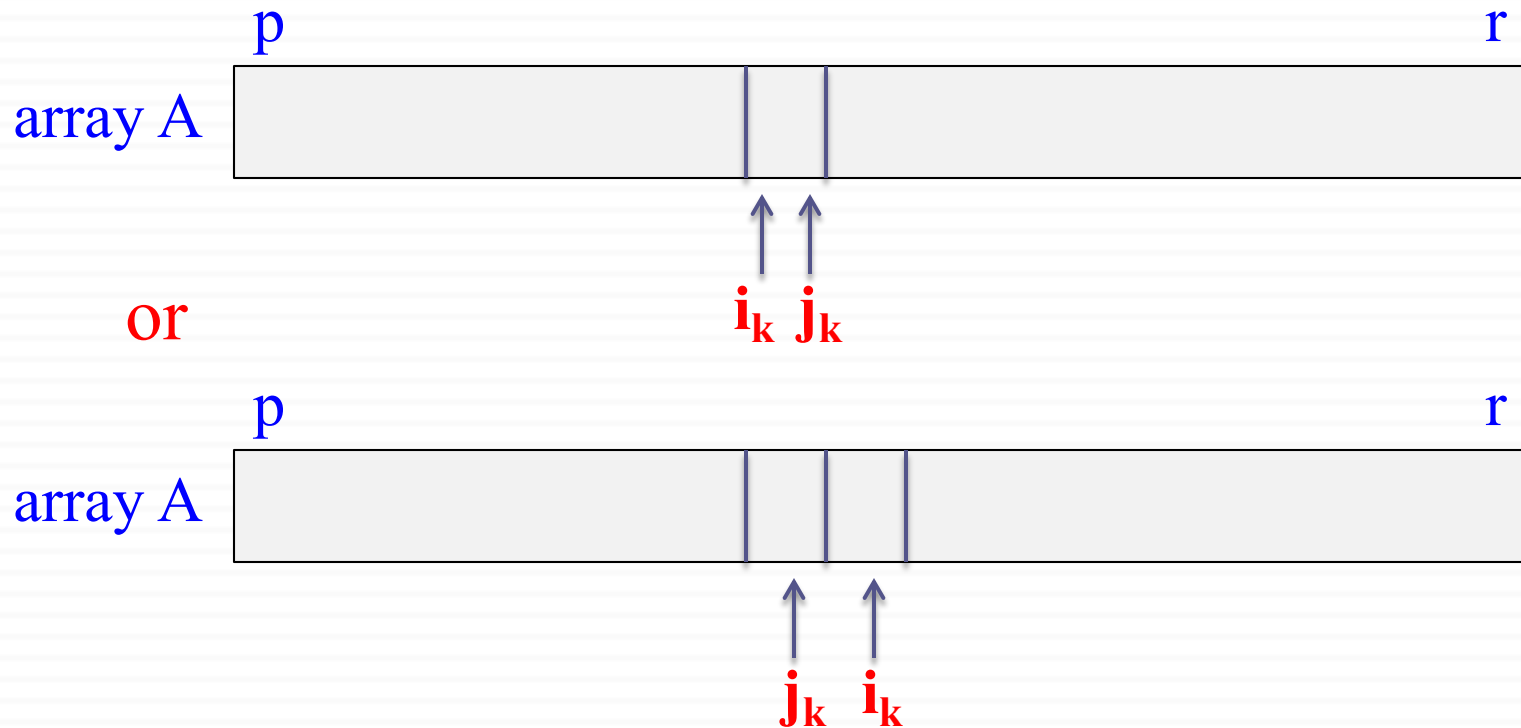
j_m : the value of index j at the end of iteration m

x : the value of the pivot element

Note: We always have $i_1 = p$ and $p \leq j_1 \leq r$
because $x = A[p]$

Correctness of Hoare's Algorithm

Lemma 1: Either $i_k = j_k$ or $i_k = j_k + 1$ at termination



Correctness of Hoare's Algorithm

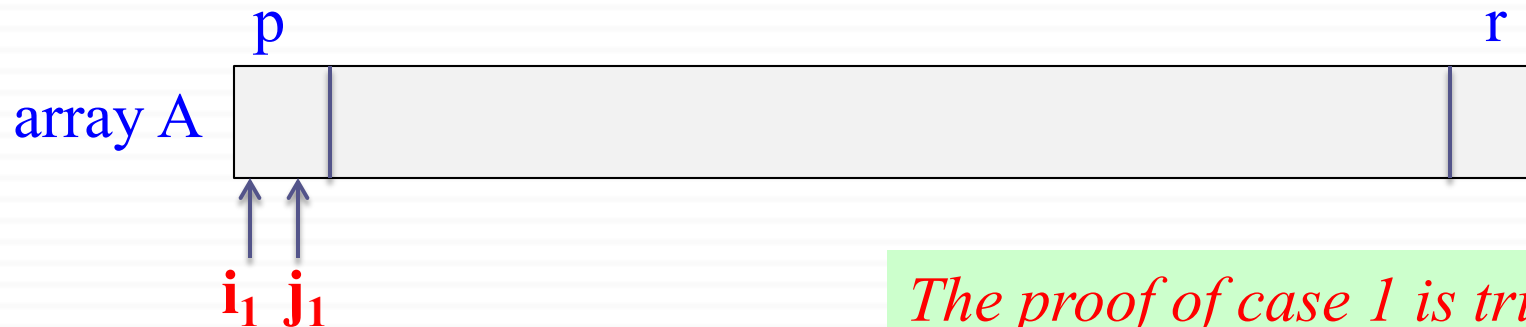
Proof of Lemma 1:

The algorithm terminates when $i \geq j$ (the else condition).

So, it is sufficient to prove that $i_k - j_k \leq 1$

There are 2 cases to consider:

Case 1: $k = 1$, i.e. the algorithm terminates in a single iteration

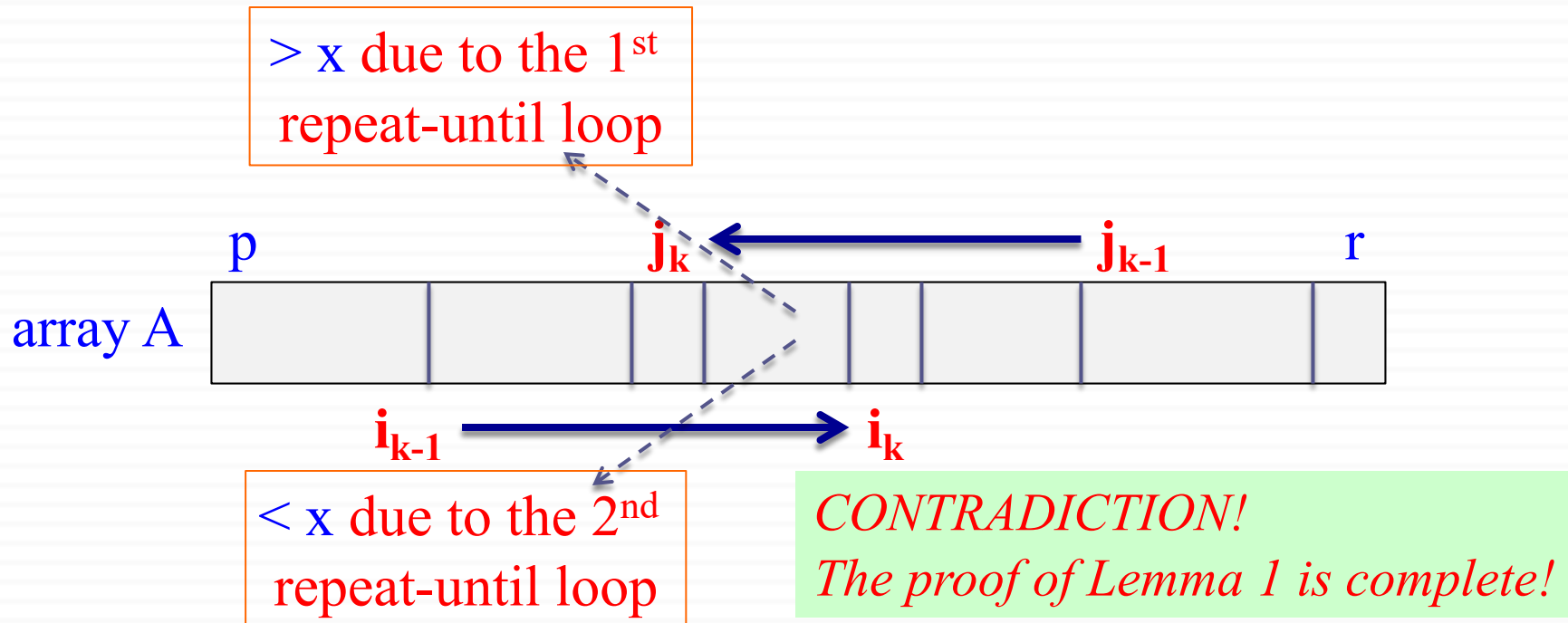


Correctness of Hoare's Algorithm

Proof of Lemma 1 (cont'd):

Case 2: $k > 1$, i.e. the alg. does not terminate in a single iter.

By contradiction, assume there is a run with $i_k - j_k > 1$



Correctness of Hoare's Algorithm

Original correctness claims:

- (a) Indices i & j never reference A outside the interval $A[p \dots r]$
- (b) Split is always non-trivial; i.e., $j \neq r$ at termination

Proof:

For $k = 1$: Trivial because $i_1 = j_1 = p$ (see *Case 1* in proof of *Lemma 2*)

For $k > 1$:

$i_k > p$ and $j_k < r$ (due to the *repeat-until loops* moving indices)

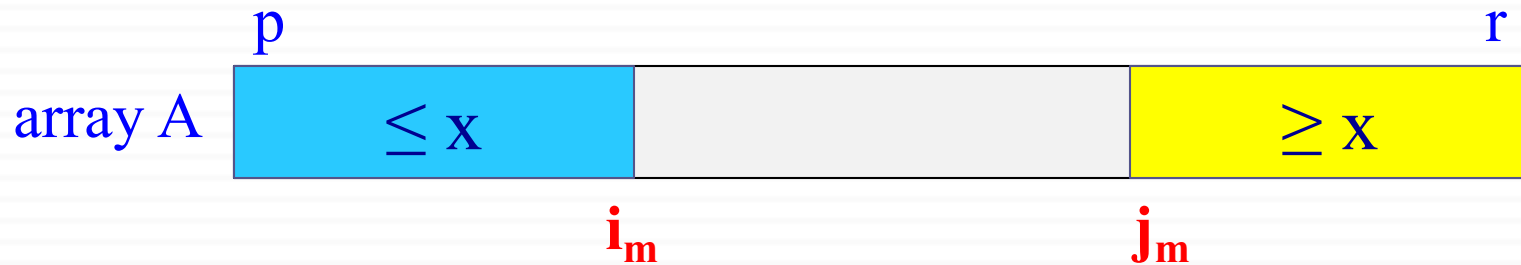
$i_k \leq r$ and $j_k \geq p$ (due to *Lemma 1* and the statement above)

➔ The proof of claims (a) and (b) complete

Correctness of Hoare's Algorithm

Lemma 2: At the end of iteration m , where $m < k$ (i.e. m is not the last iteration), we must have:

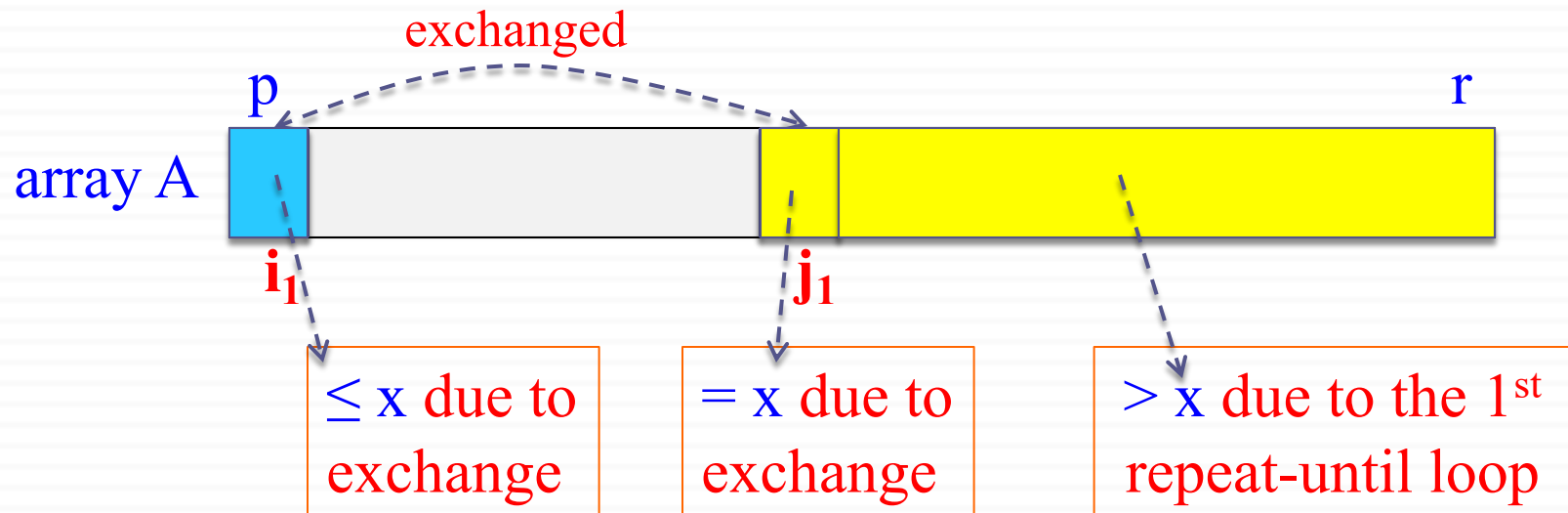
$$A[p..i_m] \leq x \quad \text{and} \quad A[j_m..r] \geq x$$



Correctness of Hoare's Algorithm

Proof of Lemma 2:

Base case: $m=1$ and $k > 1$ (i.e. the alg. does not terminate in the first iter.)



Proof of base case complete!

Correctness of Hoare's Algorithm

Proof of Lemma 2(cont'd):

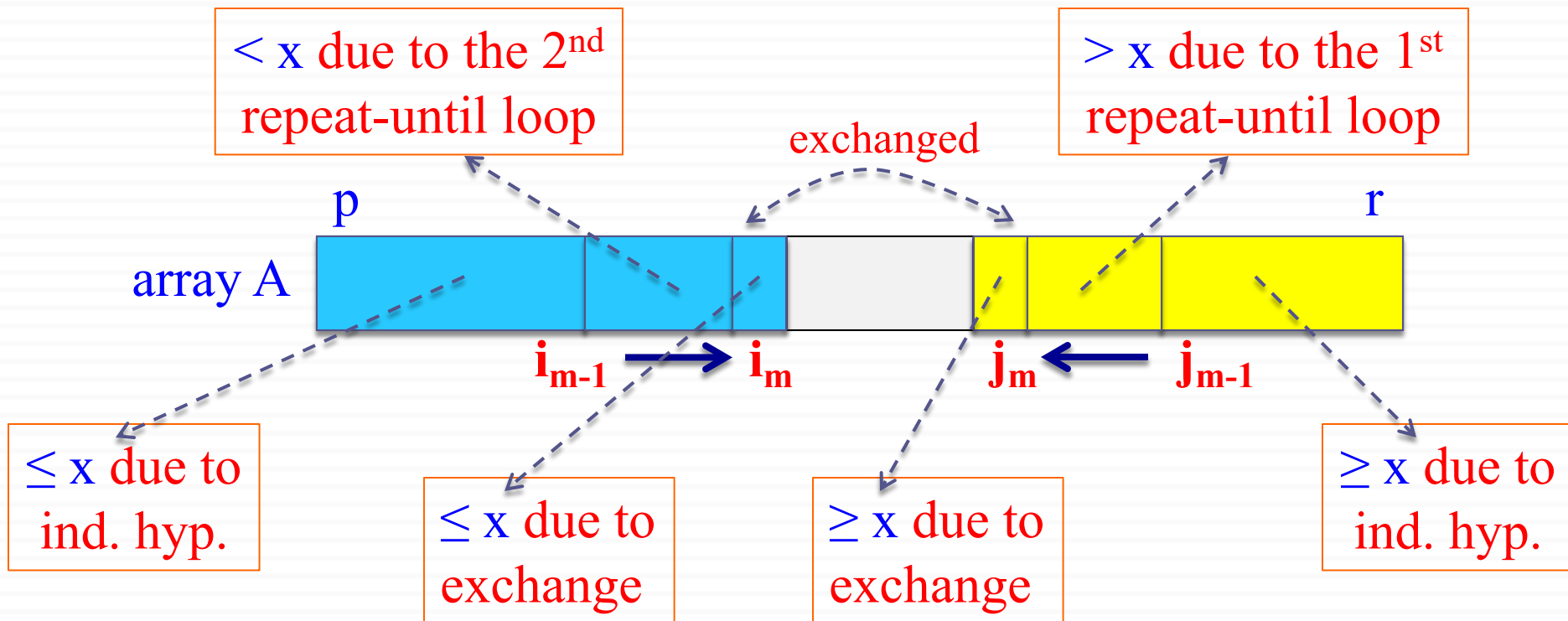
Inductive hypothesis: At the end of iteration $m-1$, where $m < k$ (i.e. m is not the last iteration), we must have:

$$A[p..i_{m-1}] \leq x \quad \text{and} \quad A[j_{m-1} .. r] \geq x$$

General case: The lemma holds for m , where $m < k$

Correctness of Hoare's Algorithm

For $1 < m < k$, at the end of iteration m , we have:



Proof of Lemma 2 complete!

Correctness of Hoare's Algorithm

Original correctness claim:

(c) Every element in $A[p..j] \leq$ every element in $A[j+1..r]$ at termination

Proof of claim (c)

There are 3 cases to consider:

Case 1: $k = 1$, *i.e. the algorithm terminates in a single iteration*

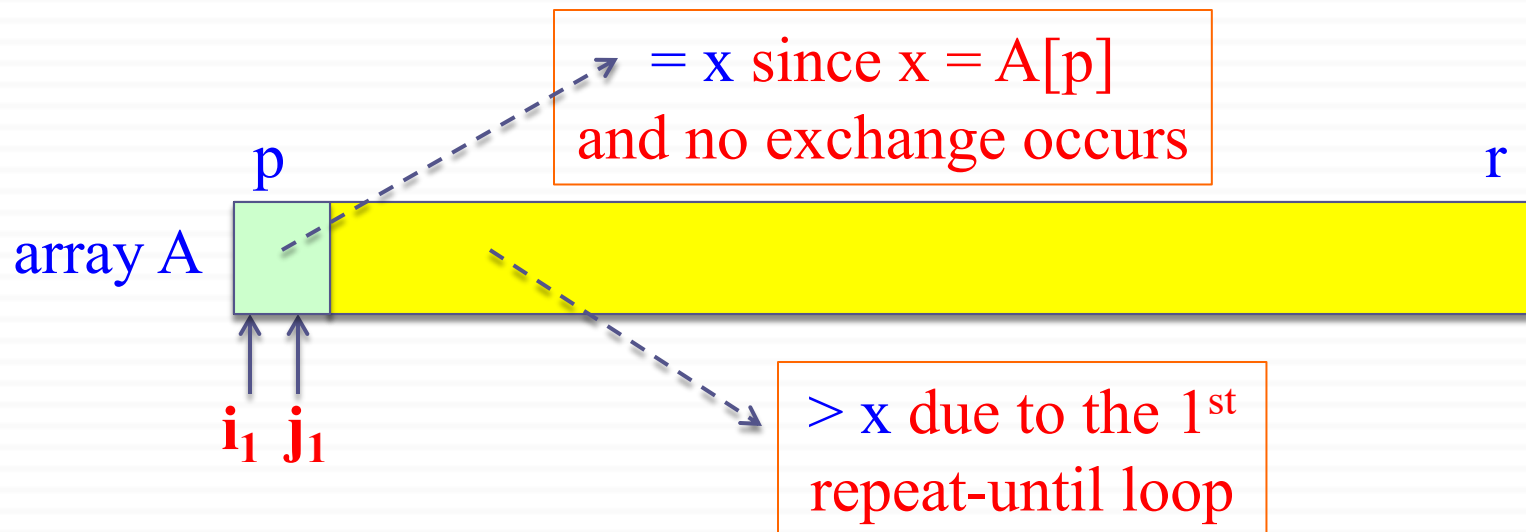
Case 2: $k > 1$ and $i_k = j_k$

Case 3: $k > 1$ and $i_k = j_k + 1$

Correctness of Hoare's Algorithm

Proof of claim (c):

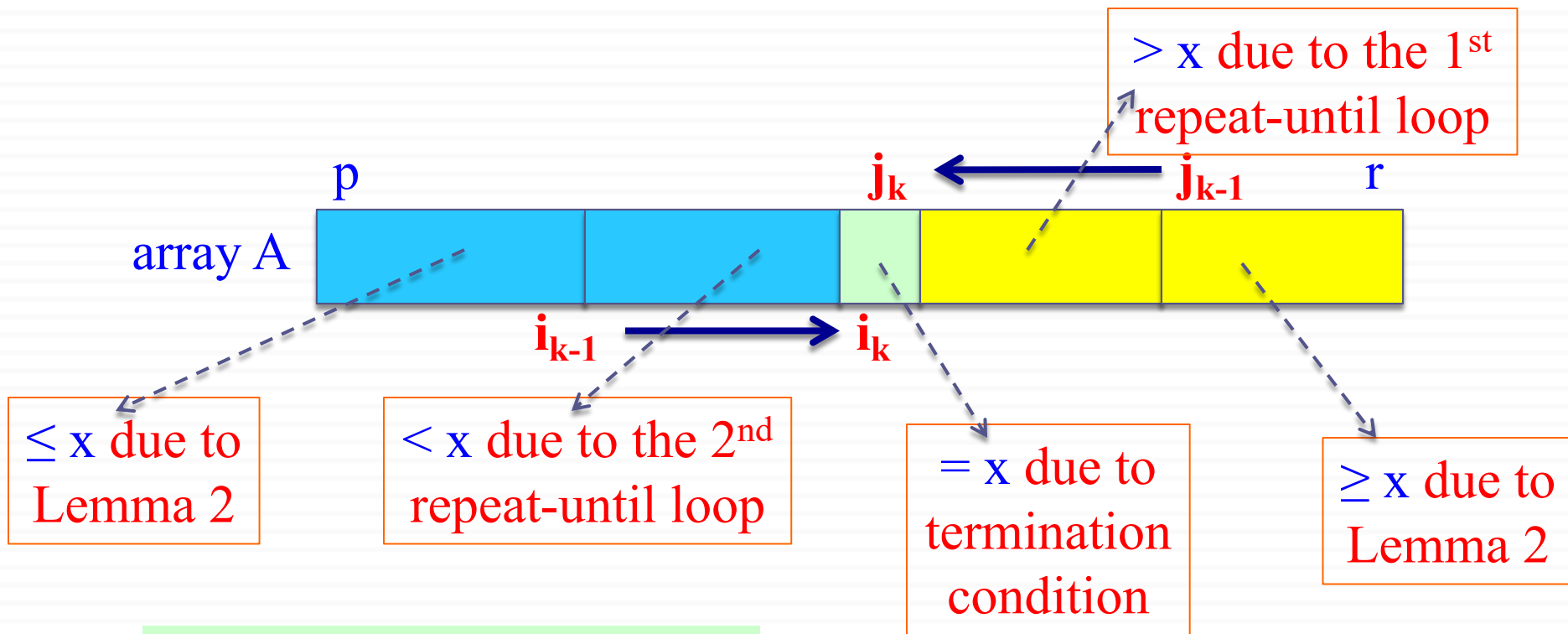
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Proof of case 1 complete!

Correctness of Hoare's Algorithm

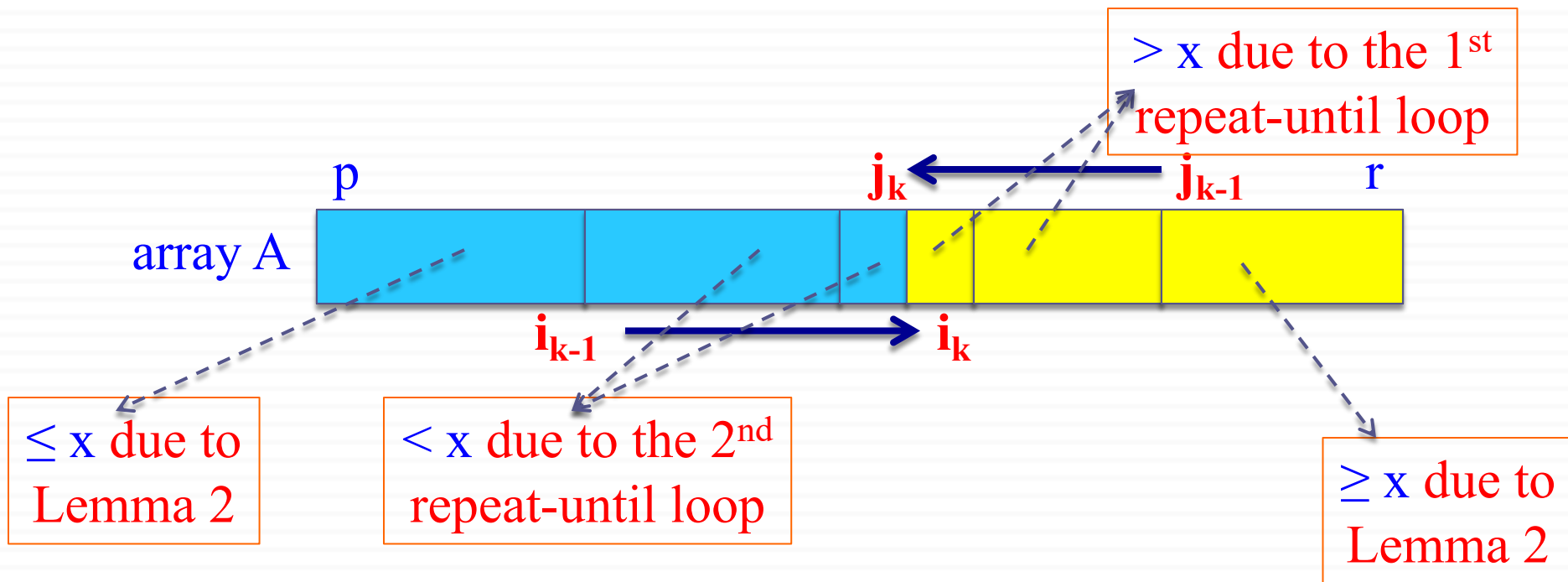
Proof of claim (c) (cont'd): Case 2: $k > 1$ and $i_k = j_k$



Proof of Case 2 complete!

Correctness of Hoare's Algorithm

Proof of claim (c) (cont'd): Case 3: $k > 1$ and $i_k = j_k + 1$

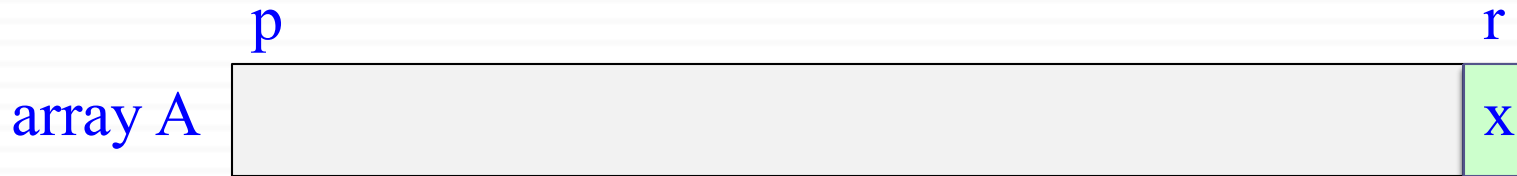


Proof of Case 3 complete!

Correctness proof complete!

Lomuto's Partitioning Algorithm

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 - from **left to right**: $A[i+1..j]$such that:
 - every element in $A[p..i] \leq \text{pivot}$
 - every element in $A[i+1..j] > \text{pivot}$



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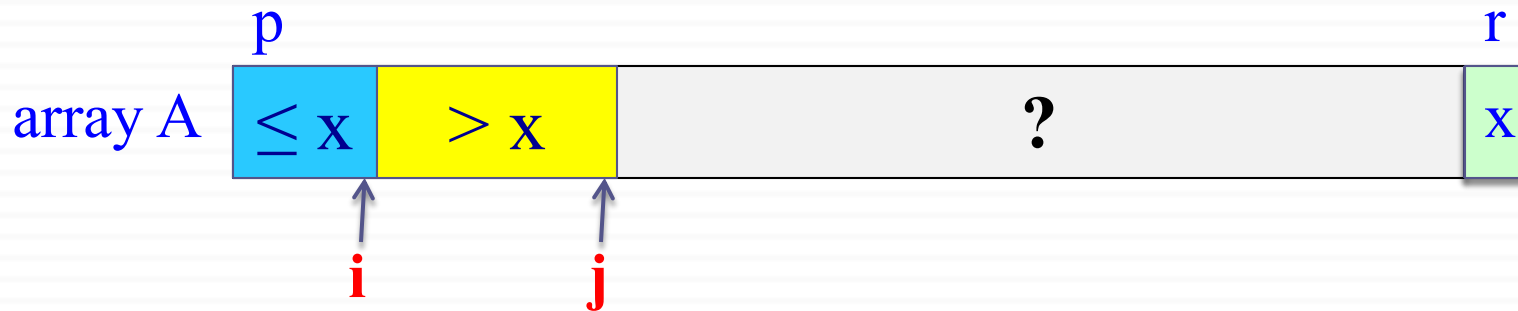
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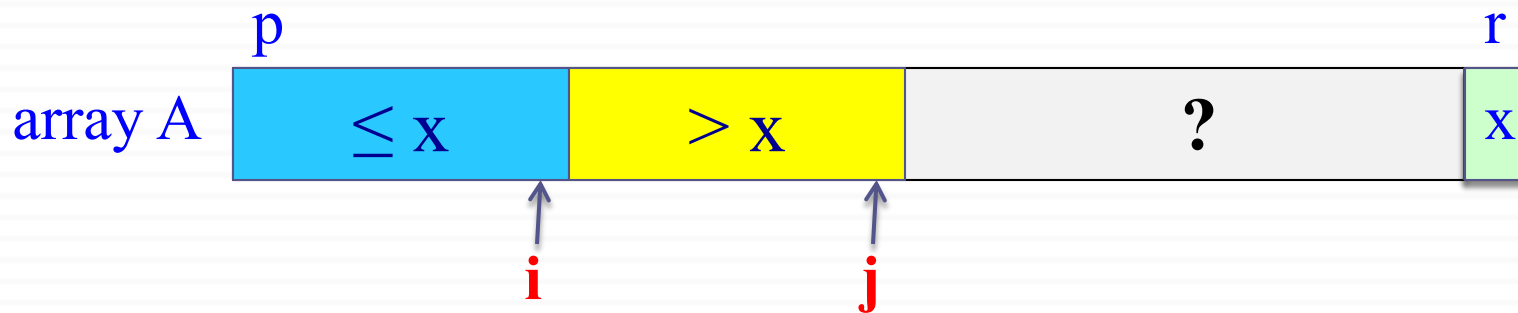
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Lomuto's Partitioning Algorithm

1. **Choose** a pivot element: $\text{pivot} = x = A[r]$

2. **Grow** two regions:

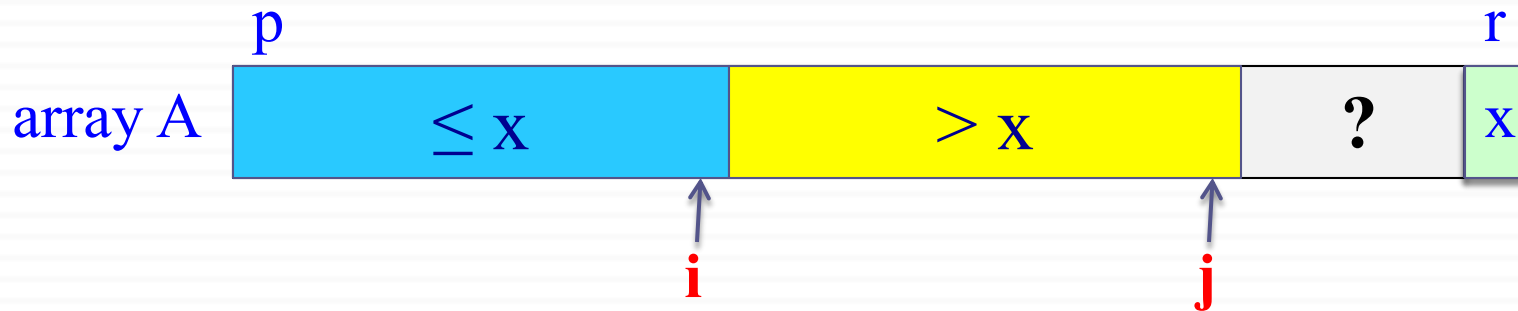
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such that:

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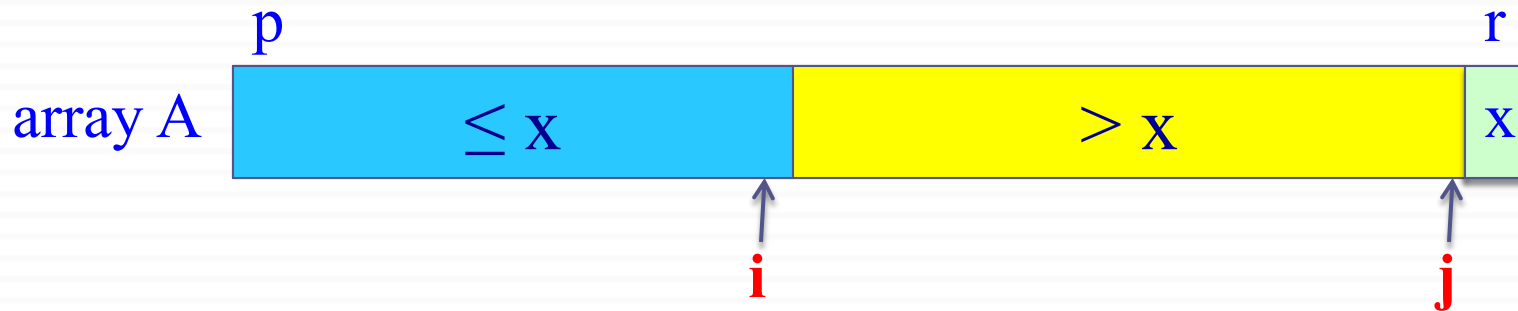
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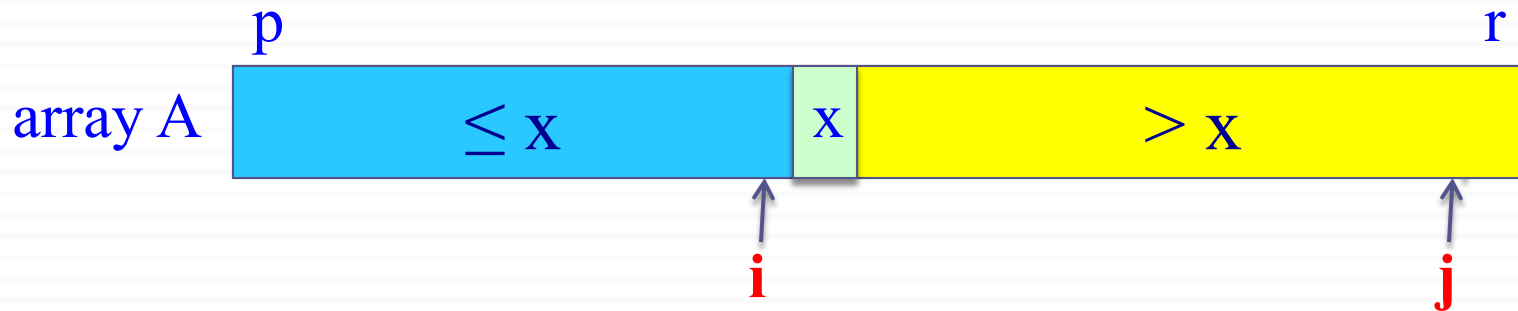
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L-PARTITION (A, p, r)

$pivot \leftarrow A[r]$

$i \leftarrow p - 1$

for $j \leftarrow p$ **to** $r - 1$ **do**

if $A[j] \leq pivot$ **then**

$i \leftarrow i + 1$

exchange $A[i] \leftrightarrow A[j]$

exchange $A[i + 1] \leftrightarrow A[r]$

return $i + 1$

array A

	p							r
	7	8	2	6	5	1	3	4

pivot = 4

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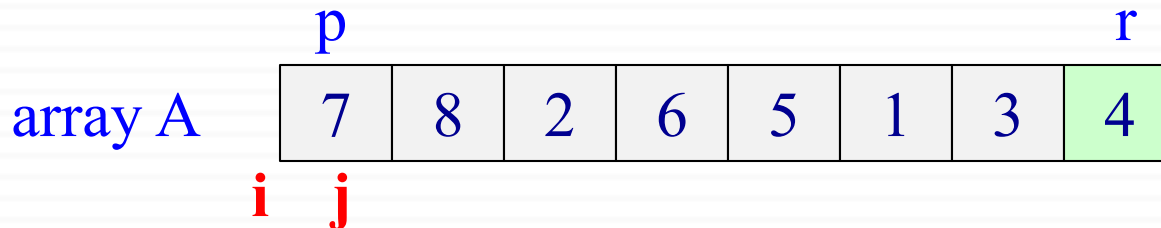
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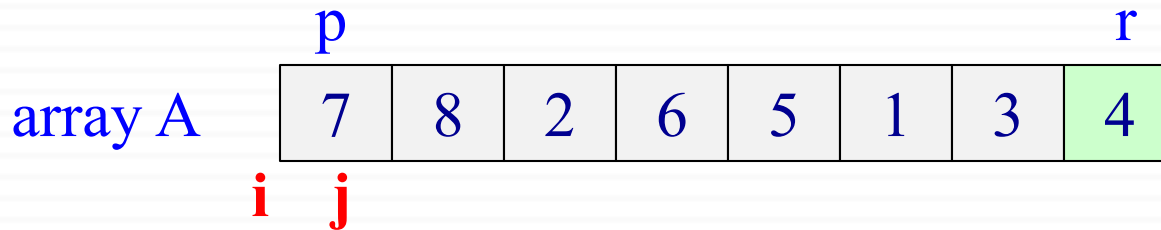
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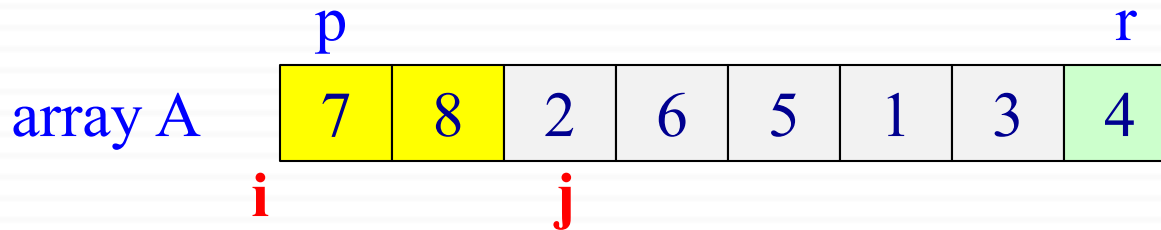
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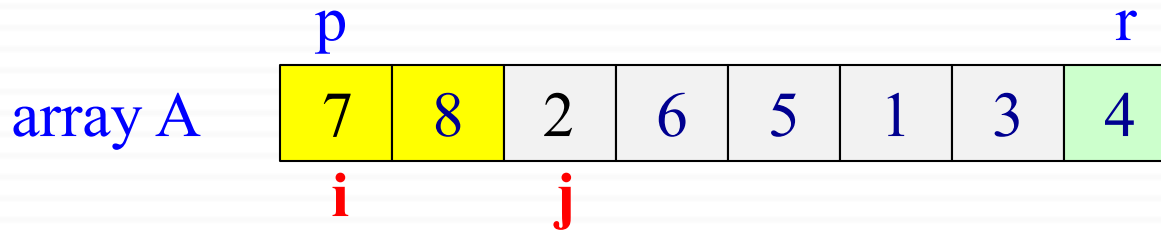
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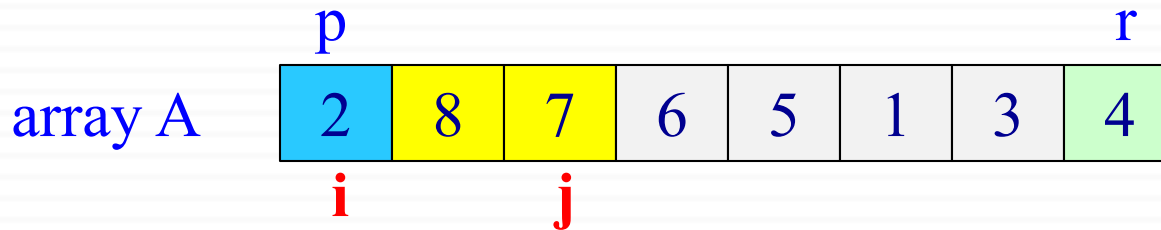
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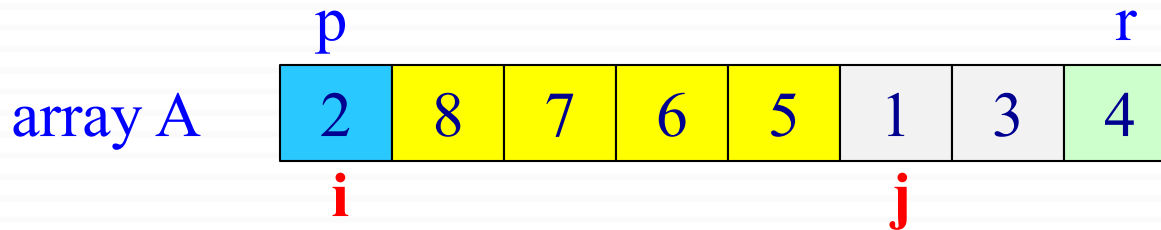
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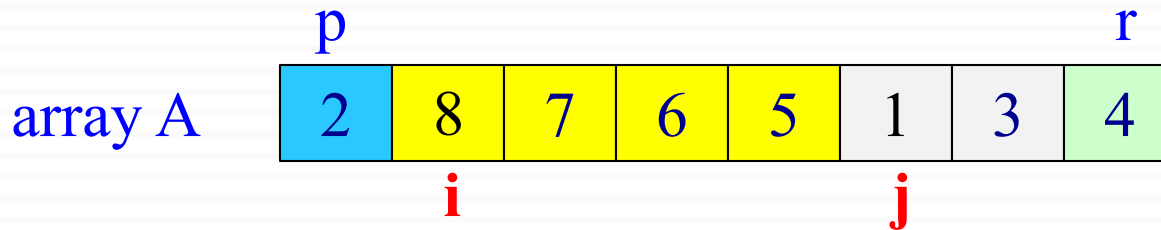
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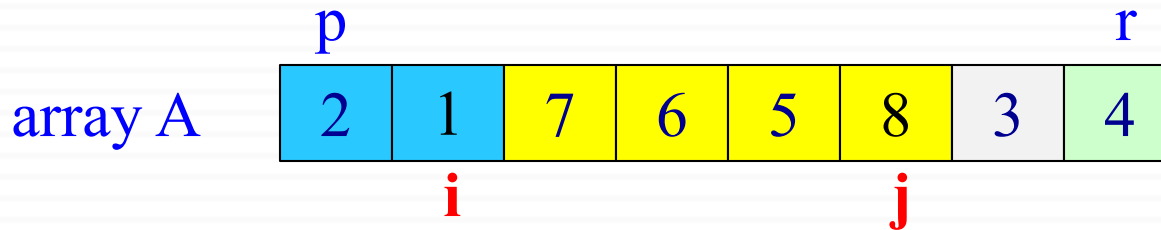
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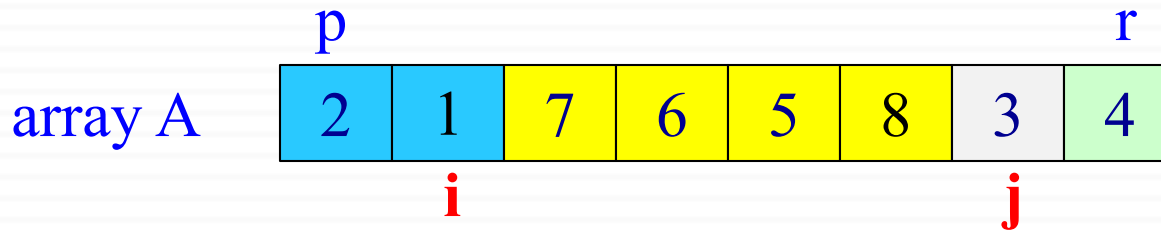
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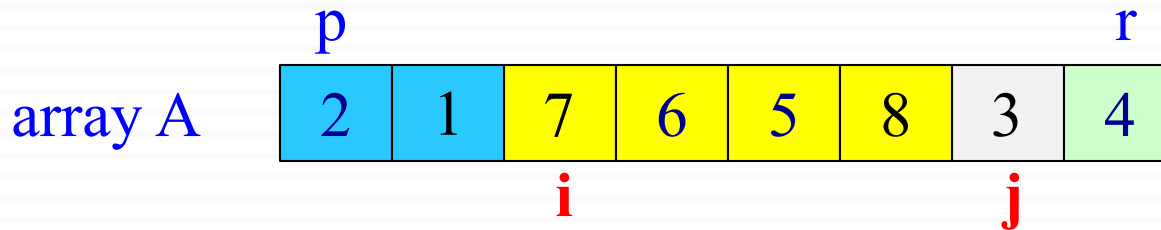
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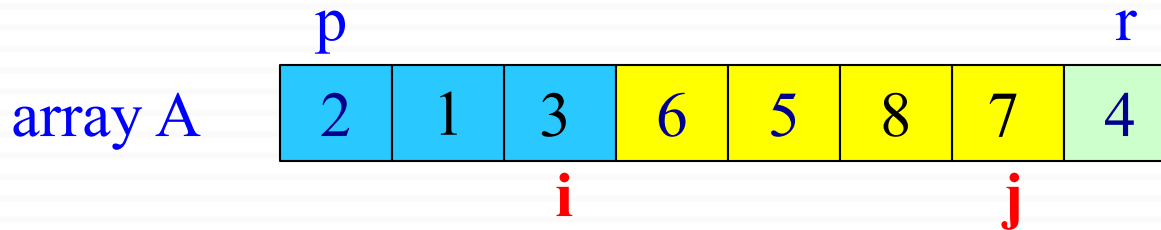
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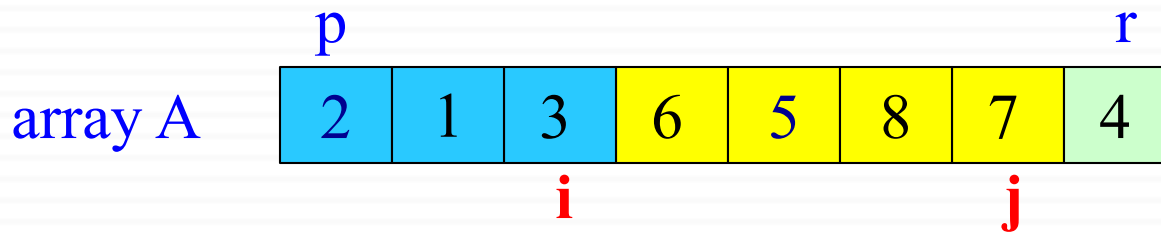
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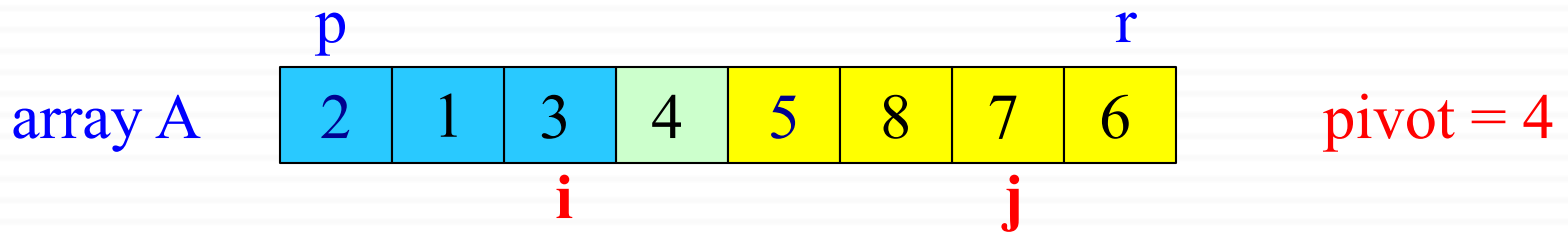
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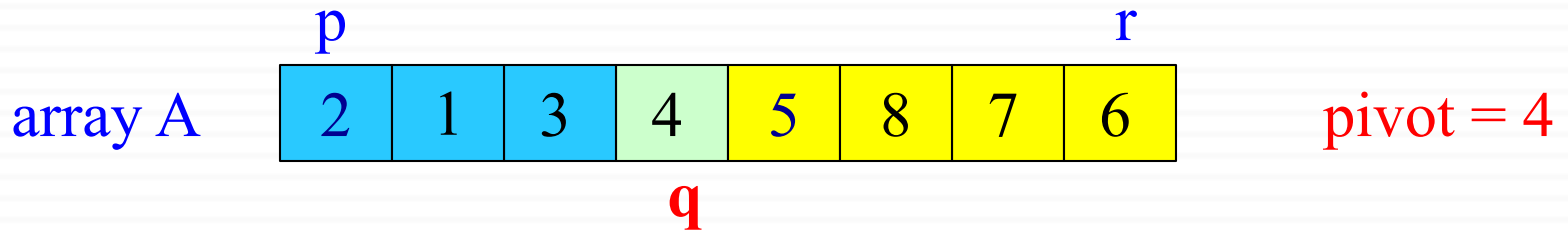
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What is the runtime of L-PARTITION? $\Theta(n)$

QUICKSORT (A, p, r)

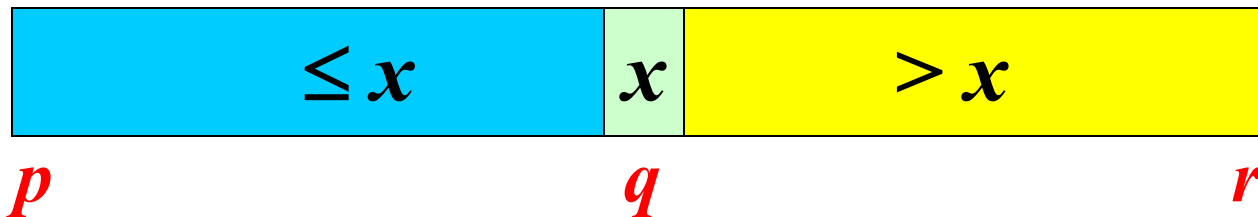
if $p < r$ then

$q \leftarrow \text{L-PARTITION}(A, p, r)$

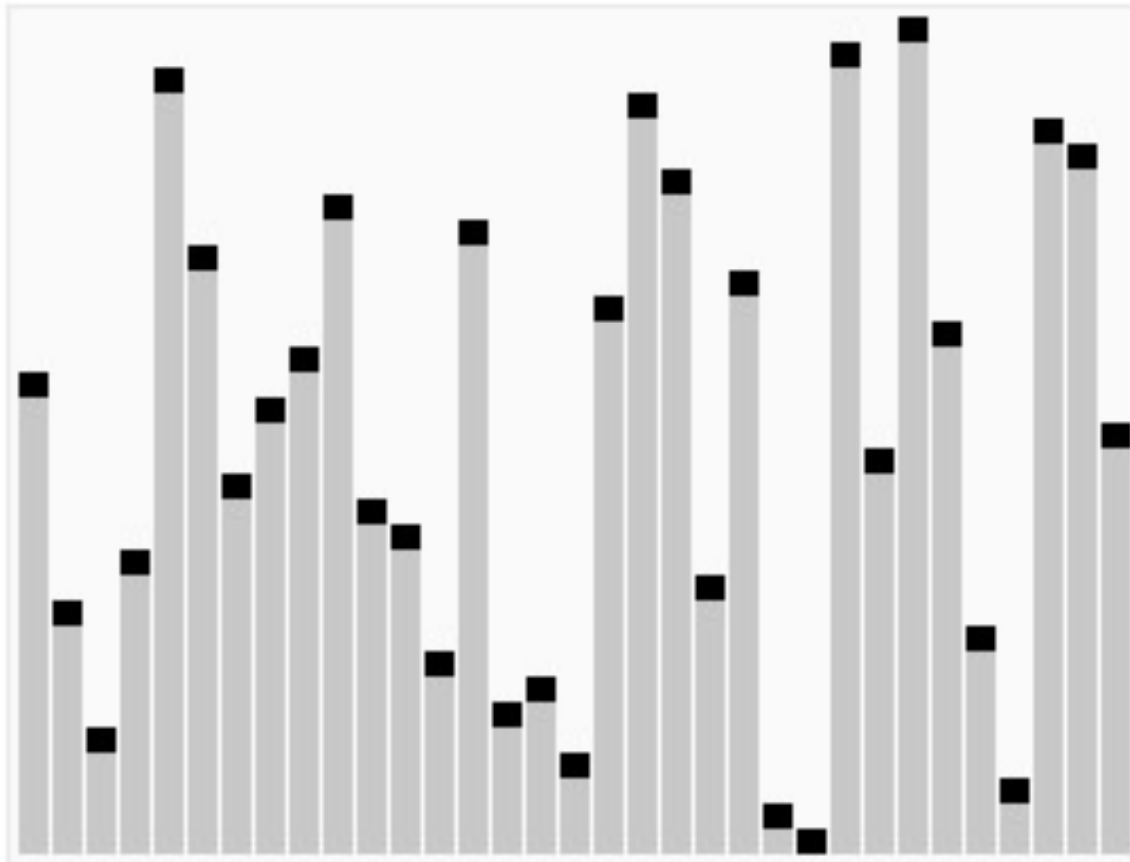
QUICKSORT($A, p, q - 1$)

QUICKSORT($A, q + 1, r$)

Initial invocation: QUICKSORT($A, 1, n$)



Quicksort Animation



from Wikimedia Commons

Comparison of Hoare's & Lomuto's Algorithms

Notation: $n = r - p + 1$ & $pivot = A[p]$ (Hoare)

& $pivot = A[r]$ (Lomuto)

➤ # of element exchanges: $e(n)$

- **Hoare:** $0 \leq e(n) \leq \left\lfloor \frac{n}{2} \right\rfloor$
 - **Best:** $k = 1$ with $i_1 = j_1 = p$ (i.e., $A[p+1 \dots r] > pivot$)
 - **Worst:** $A[p+1 \dots p + \left\lfloor \frac{n}{2} \right\rfloor - 1] \geq pivot \geq A[p + \left\lceil \frac{n}{2} \right\rceil \dots r]$
- **Lomuto:** $1 \leq e(n) \leq n$
 - **Best:** $A[p \dots r-1] > pivot$
 - **Worst:** $A[p \dots r-1] \leq pivot$

Comparison of Hoare's & Lomuto's Algorithms

➤ # of element comparisons: $c_e(n)$

- Hoare: $n + 1 \leq c_e(n) \leq n + 2$

- Best: $i_k = j_k$

- Worst: $i_k = j_k + 1$

- Lomuto: $c_e(n) = n - 1$

➤ # of index comparisons: $c_i(n)$

- Hoare: $1 \leq c_i(n) \leq \left\lfloor \frac{n}{2} \right\rfloor + 1 \quad (c_i(n) = e(n) + 1)$

- Lomuto: $c_i(n) = n - 1$

Comparison of Hoare's & Lomuto's Algorithms

- # of index increment/decrement operations: $a(n)$
 - **Hoare:** $n + 1 \leq a(n) \leq n + 2$ ($a(n) = c_e(n)$)
 - **Lomuto:** $n \leq a(n) \leq 2n - 1$ ($a(n) = e(n) + (n - 1)$)
- Hoare's algorithm is in general faster
- Hoare behaves better when pivot is repeated in $A[p \dots r]$
 - **Hoare:** Evenly distributes them between left & right regions
 - **Lomuto:** Puts all of them to the left region