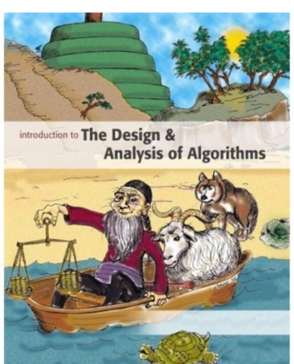
Introduction to

Algorithm Design and Analysis

[7] Selection



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In the last class…

- **MergeSort**
  - Design
  - Cost – time & space
  - MergeSort DC

- **Lower bounds for comparison-based sorting**
  - Worst-case
  - Average-case

Selection

- **Selection – warm-ups**
  - Finding *max* and *min*
  - Finding the *second largest* key
- **Lower bound and *adversary argument***

- **Selection – select the *median***
  - Expected linear time
  - Worst-case linear time
- **A Lower Bound for Finding the Median**

The Selection Problem

- **Problem definition**
  - Suppose E is an array containing n elements with keys from some linearly order set, and let k be an integer such that $1 \leq k \leq n$. The selection problem is to find an element with the k^{th} smallest key in E.
- **Special cases**
  - Find the max/min – $k=n$ or $k=1$
  - Find the *median* ($k = \frac{n}{2}$)

Selection
vs.
Searching

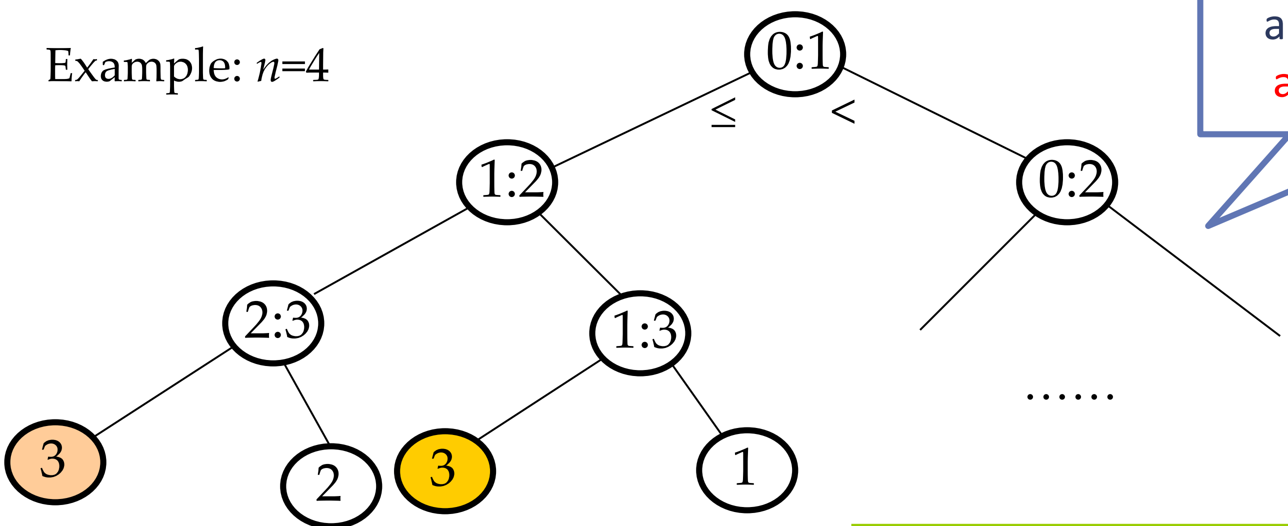
Lower Bound of Finding the Max

- **For any algorithm $\mathcal{A}$ that can compare and copy numbers exclusively, in the worst case, $\mathcal{A}$ cannot do fewer than n-1 comparisons to find the largest entry in an array with n entries.**
  - Proof: an array with n distinct entries is assumed. We can exclude a specific entry from being the largest entry only after it is determined to be "loser" to at least one entry. So, n-1 entries must be "losers" in comparisons done by the algorithm. However, each comparison has only one loser, so at least n-1 comparisons must be done.

Decision Tree and Lower Bound

Since the decision tree for the selection problem must have at least n leaves, the height of the tree is at least $\lceil \log n \rceil$. **It is not a good lower bound.**

Example: n=4



A more powerful tool for analysis is necessary: adversary argument

There are more than n leaves! In fact, 2^{n-1} leaves at least.

Finding *max* and *min*

- **The strategy**
  - Pair up the keys, and do $n/2$ comparisons(if n odd, having E[n] uncompared);
  - Doing findMax for larger key set and findMin for small key set respectively (if n odd, E[n] included in both sets)
- **Number of comparisons**
  - For even n: $n/2+2(n/2-1)=3n/2-2$
  - For odd n: $(n-1)/2+2((n-1)/2+1-1)=\lceil 3n/2 \rceil-2$

How to prove this lower bound?

Adversary Argument !

Unit of Information

- **Max and Min**
  - That x is *max* can only be known when it is sure that every key other than x has lost some comparison.
  - That y is *min* can only be known when it is sure that every key other than y has win some comparison.
- **Each win or loss is counted as one unit of information**
  - *Any* algorithm must have at least $2n$-2 units of information to be sure of specifying the *max* and *min*.

Adversary Strategy

Status of keys x and y Compared by an algorithm	Adversary response	New status	Units of new information
N,N	$x>y$	W,L	2
W,N or WL,N	$x>y$	W,L or WL,L	1
L,N	$x<y$	L,W	1
W,W	$x>y$	W,WL	1
L,L	$x>y$	WL,L	1
W,L or WL,L or W,WL	$x>y$	No change	0
WL,WL	Consistent with Assigned values	No change	0

The principle: let the key win if it never lose, or,
let the key lose if it never win, and

change one value if necessary

Lower Bound by the Adversary Argument

- **Construct an input to force *the* algorithm to do more comparisons as possible**
  - To give away as few as possible units of new information with each comparison.
    - It can be achieved that 2 units of new information are given away only when the status is N,N.
    - It is ***always*** possible to give adversary response for other status so that at most one new unit of information is given away, ***without any inconsistencies***.
- **So, the *Lower Bound* is $n/2+n-2$(for even n)**

$$\boxed{\frac{n}{2} \times 2 + (n-2) \times 1 = 2n - 2}$$

An Example

Comparison	x_1 S	x_1 V	x_2 S	x_2 V	x_3 S	x_3 V	x_4 S	x_4 V	x_5 S	x_5 V	x_6 S	x_6 V
x_1,x_2					N	*	N	*	N	*	N	*
x_1,x_5									L	5		
x_3,x_4												
x_3,x_6											L	12
x_3,x_1												
x_2,x_4												
x_5,x_6									WL	5	L	3
x_6,x_4							L	2			WL	3

Now, x_3 is the only one which never loses, so, Max is x_3

8 comparisons!

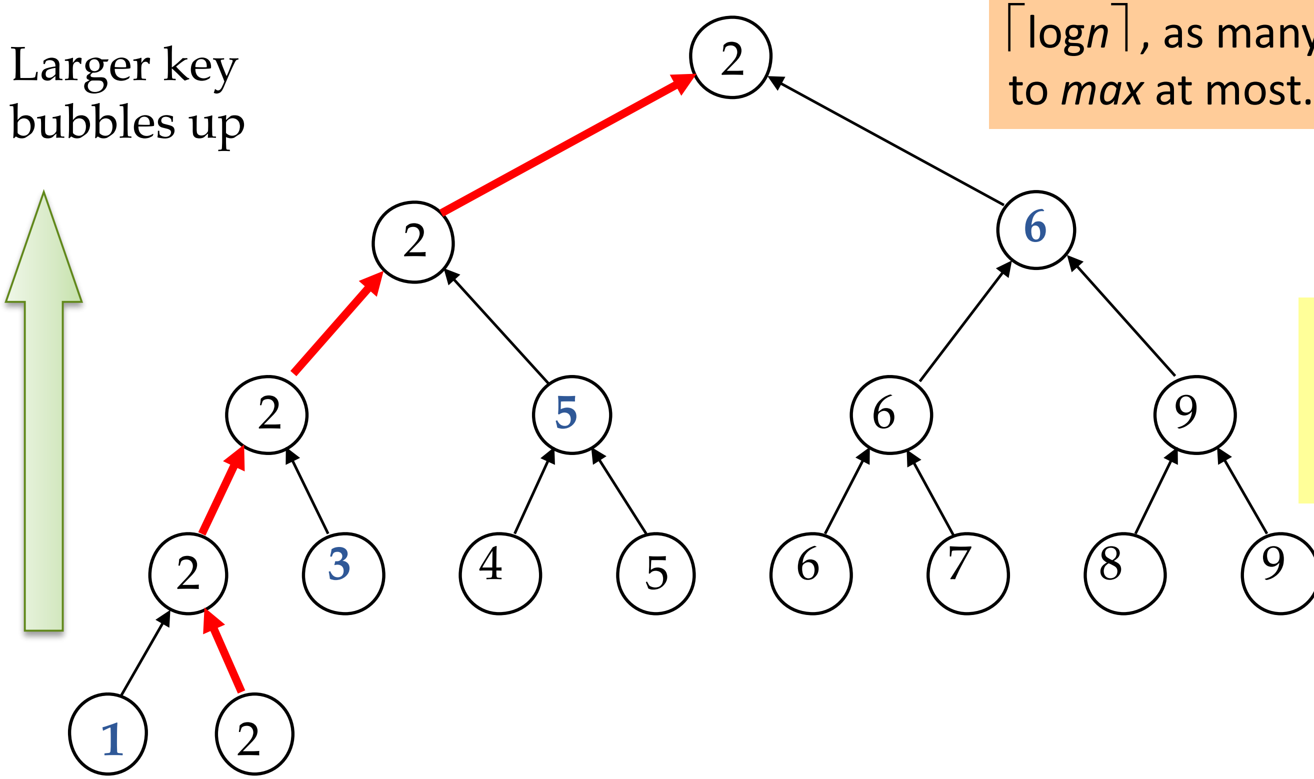
The lower bound is 7.

Raising/lowering the value according to strategy

Find the 2nd Largest Key

- **Brute force - using FindMax twice**
  - Need 2n-3 comparisons.
- **For a better algorithm**
  - Collect some useful information from the first FindMax
- **Observations**
  - The key which loses to a key other than max cannot be the 2nd largest key.
  - To check "whether you lose to max?"

Tournament for the 2nd Largest Key



The length of the longest path is $\lceil \log n \rceil$, as many as those compared to *max* at most.

x_2 is *max*

Only x_1, x_3, x_5, x_6 may be the second largest key.

Analysis of Finding the 2nd

- Any algorithm that finds *secondLargest* must also find *max* before. **(n-1)**
- The *secondLargest* can only be in those which lose directly to *max*.
- On its path along which bubbling up to the root of tournament tree, *max* beat $\lceil \log n \rceil$ keys at most.
- Pick up *secondLargest* **($\lceil \log n \rceil$-1)**
- Total cost: $n+\lceil \log n \rceil-2$

Lower Bound by Adversary

- **Theorem**
  - Any algorithm (that works by comparing keys) to find the second largest in a set of n keys must do at least $n+\lceil \log n \rceil-2$ comparisons in the worst case.
- **Proof**
  - There is an adversary strategy that can force any algorithm that finds *secondLargest* to compare *max* to $\lceil \log n \rceil$ distinct keys.

Weighted Key

- **Assigning a weight $w(x)$ to each key**
  - The initial values are all 1.
- **Adversary strategy**

Note: for one comparison, the weight increasing is no more than doubled.

Case	Adversary reply	Updating of weights
$w(x)>w(y)$	x>y	$w(x):=w(x)+w(y)$; $w(y):=0$
$w(x)=w(y)>0$	$x>y$	$w(x):=w(x)+w(y)$; $w(y):=0$
$w(y)>w(x)$	$y>x$	$w(y):=w(x)+w(y)$; $w(x):=0$
$w(x)=w(y)=0$	Consistent with previous replies	No change

Zero loss

Lower Bound by Adversary: Details

- Note: the sum of weights is always n.
- Let x is max, then x is the only nonzero weighted key, that is $w(x)=n$.
- By the adversary rules:

$$w_k(x) \leq 2w_{k-1}(x)$$

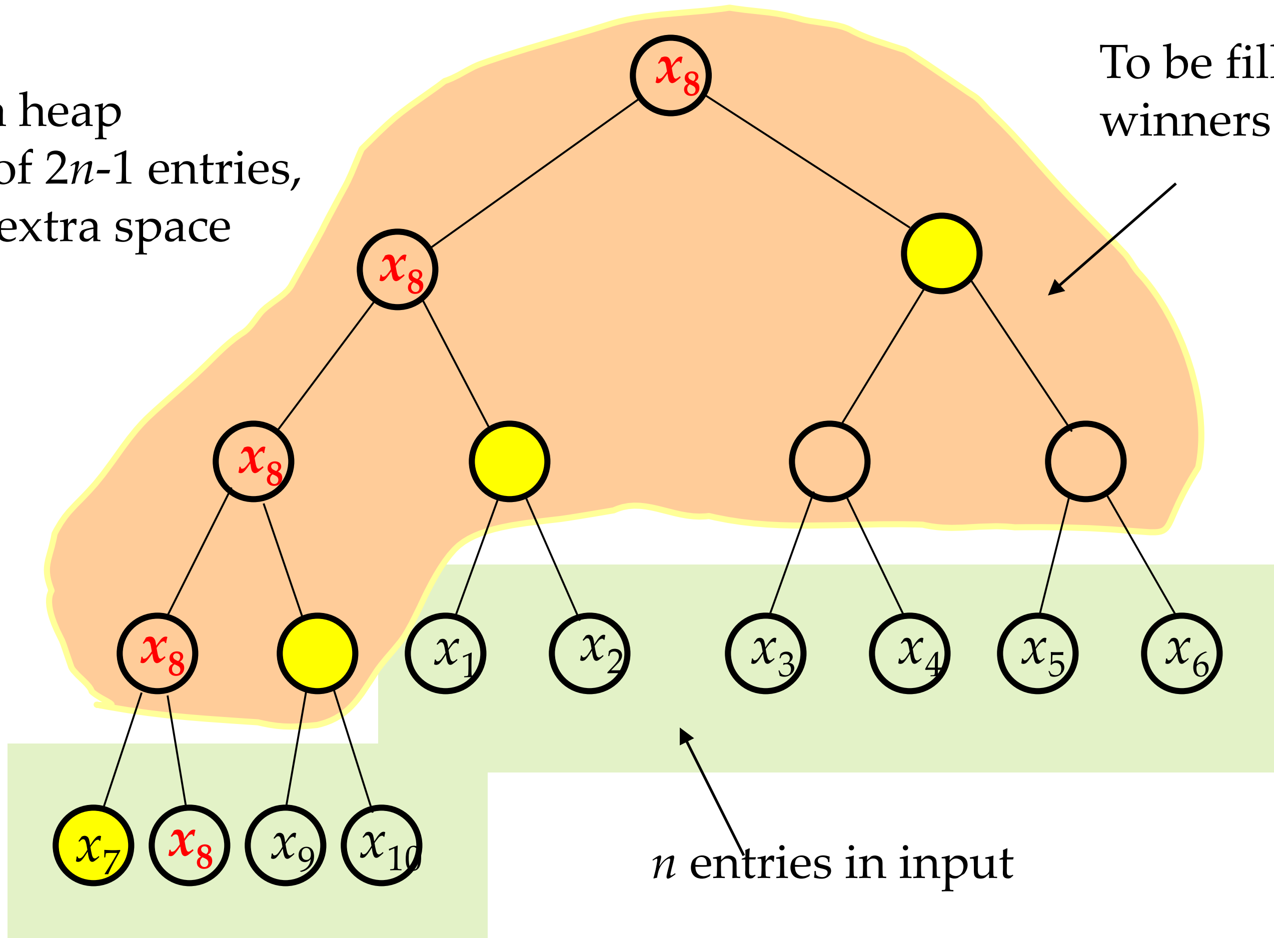
- Let K be the number of comparisons x wins against previously undefeated keys:

$$n = w_K(x) \leq 2^K w_0(x) = 2^K$$

- So, $K \geq \lceil \log n \rceil$

Tracking the Losers to *MAX*

Building a heap structure of $2n$-1 entries, using n-1 extra space



To be filled with winners

n entries in input

Finding the Median: the Strategy

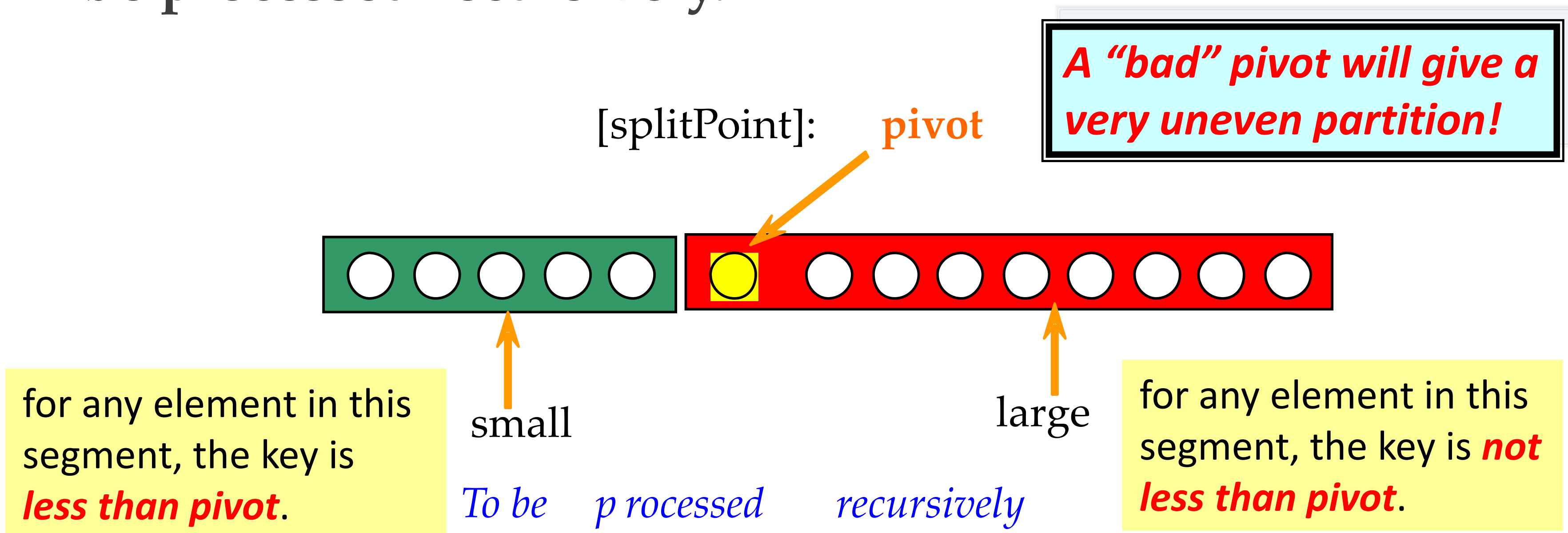
- **Observation**
  - If we can partition the problem set of keys into 2 subsets: S1, S2, such that any key in S1 is smaller that that of S2, the median must located in the set with more elements.
- **Divide-and-Conquer**
  - Only one subset is needed to be processed recursively.

Adjusting the Rank

- **The rank of the median (of the original set) in the subset considered can be evaluated easily.**
- **An example**
  - Let n=255
  - The rank of median we want is 128
  - Assuming $|S_1|$=96, $|S_2|$=159
  - Then, the original median is in S_2, and the new rank is 128-96=32

Partitioning: Larger and Smaller

- **Dividing the array to be considered into two subsets: "small" and "large", the one with more elements will be processed recursively.**



Selection: the Algorithm

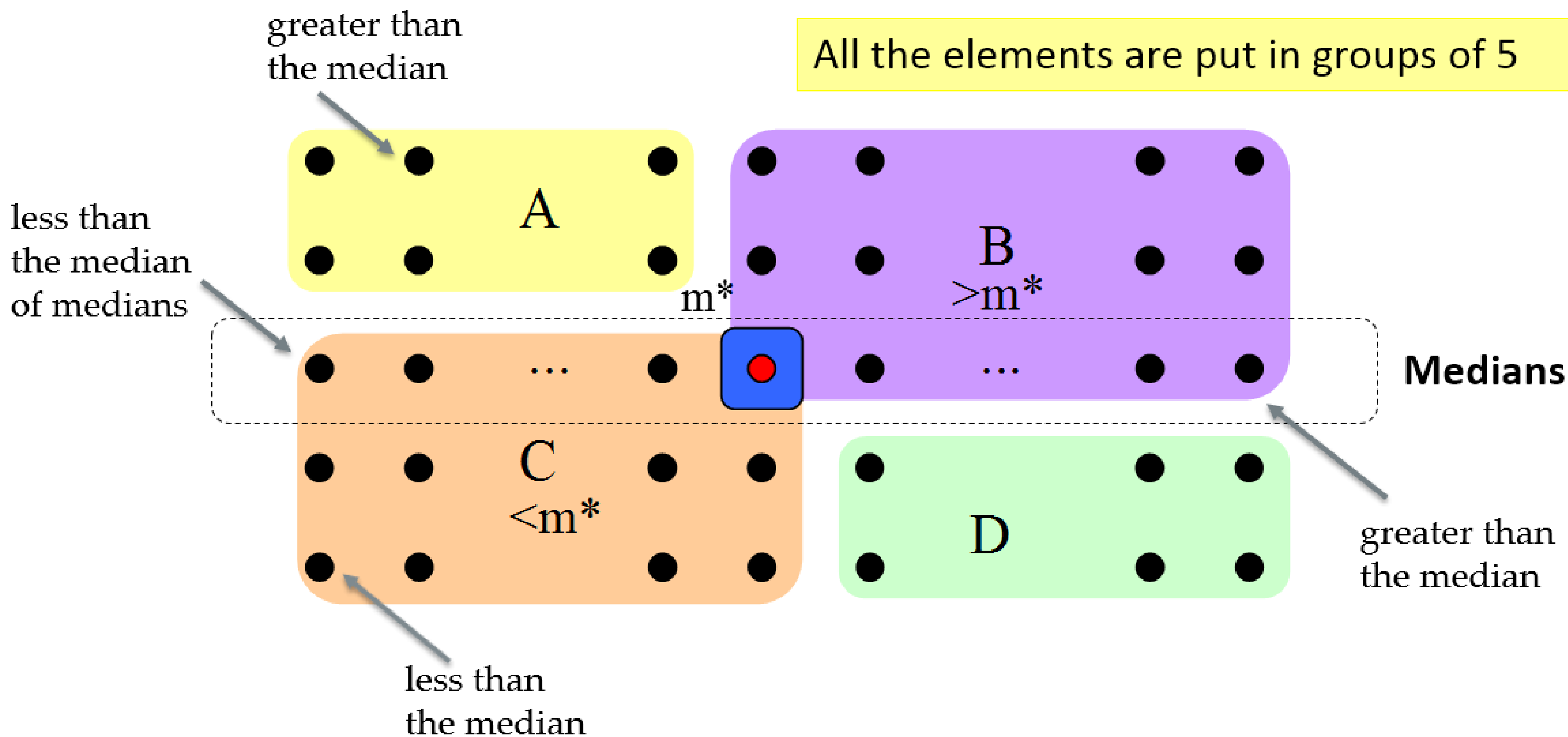
- **Input: *S*, a set of *n* keys; and *k*, an integer such that $1 \le k \le n$.**
- **Output: The *k*th smallest key in *S*.**
- **Note: Median selection is only a special case of the algorithm, with $k = \lceil n/2 \rceil$.**
- **Procedure**
- **Element select(SetOfElements *S*, int *k*)**
  - **if** ($|S| \le 5$) **return** direct solution; **else**
  - Constructing the subsets S_1 and S_2;
  - Processing one of $\boldsymbol{S_1, S_2}$ with more elements, recursively.

Key issue:

How to construct the **partition** ?

Partition improved: the Strategy

All the elements are put in groups of 5



Constructing the Partition

- **Find the m^*, the median of medians of all the groups of 5, as illustrated previously.**
- **Compare each key in sections A and D to m^*, and**
  - Let $S_1 = C \cup \{x \mid x \in A \cup D \text{ and } x < m^*\}$
  - Let $S_2 = B \cup \{x \mid x \in A \cup D \text{ and } x > m^*\}$

  (m^* is to be used as the pivot for the partition)

Divide and Conquer

if (k=|S_1|+1)

    return m^*;

else if ($k \leq$|S_1|)

    return select(S_1,k); //recursion

else

    return select(S_2,k-|S_1|-1); //recursion

Analysis

- **For simplicity:**
  - o Assuming n=5(2r+1) for all calls of *select*.
- $$W(n) \le 6\left(\frac{n}{5}\right) + W\left(\frac{n}{5}\right) + 4r + W(7r+2)$$

The extreme case: all the elements in A∪D in one subset.

Finding the median in every group of 5

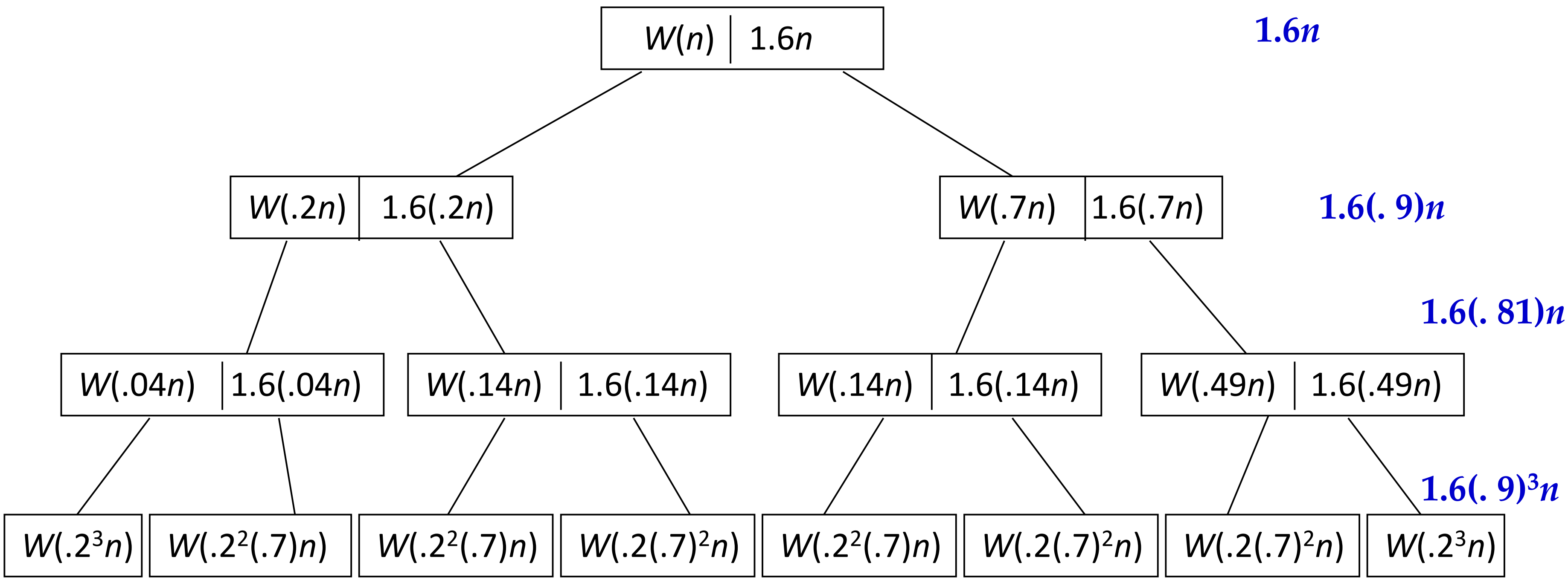
Finding the median of the medians

Comparing all the elements in A∪D with *m**

- ***Note: r is about n/10, and 0.7n+2 is about 0.7n*, so**

$$W(n) \le 1.6n + W(0.2n) + W(0.7n)$$

Worst Case Complexity of *Select*

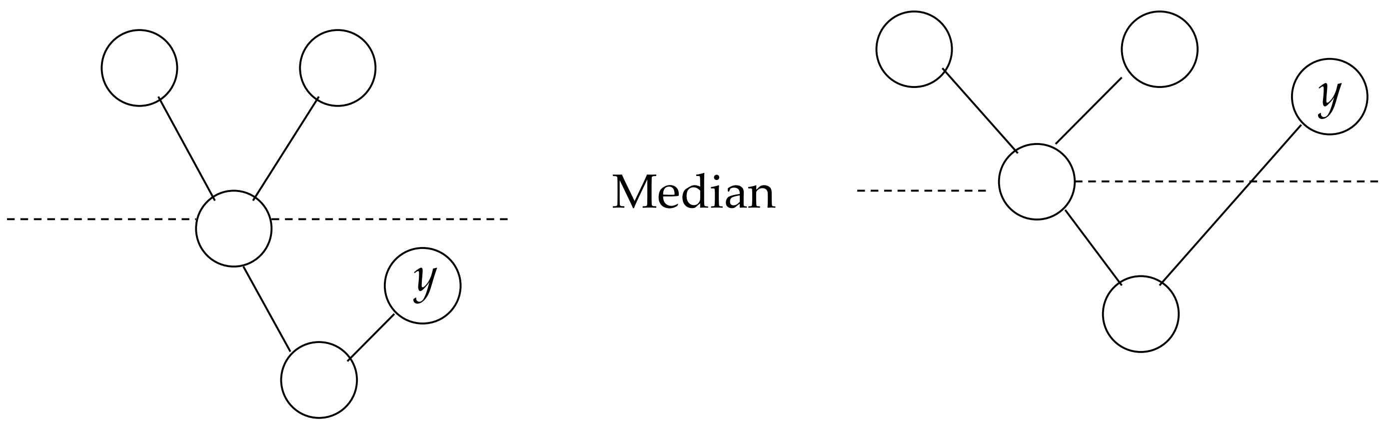


Note: Row sums is a decreasing geometric series, so

$W(n) \in \Theta(n)$

Relation to Median

- **Observation**
  - Any algorithm of selection must know the relation of every element to the *median*.



The adversary makes you wrong in either case

Crucial Comparison

- A **crucial comparison**
  - Establishing the relation of some x to the median.
- **Definition (for a comparison involving a key x)**
  - Crucial comparison for x: the first comparison where $x>y$, for some $y \geq$median, or $x<y$ for some $y \leq$median
  - Non-crucial comparison: the comparison between x and y where $x>$median and $y<$median， or vise versa

Adversary for Lower Bound

- **Status of the key during the running of the Algorithm:**
  - L: Has been assigned a value ***larger*** than median
  - S: Has been assigned a value ***smaller*** than median
  - N: Has not yet been in a comparison

- **Adversary rule:**

Comparands	**Adversary's action**
N*,*N	**one *L*, the another *S***
L*,*N* or *N*,*L	**change *N* to *S***
S*,*N* or *N*,*S	**change *N* to *L***

(In all other cases, just keep consistency)

Notes on the Adversary Arguments

- **All actions explicitly specified above make the comparisons un-crucial.**
  - At least, (n-1)/2 L or S can be assigned freely.
  - If there are already (n-1)/2 S, a value larger than median must be assigned to the new key, and if there are already (n-1)/2 L, a value smaller than median must be assigned to the new key. The last assigned value is the median.
- **So, an adversary can force the algorithm to do (n-1)/2 un-crucial comparisons at least(In the case that the algorithm start out by doing (n-1)/2 comparisons involving two N.**

Lower Bound for Selection Problem

- **Theorem:**
  - Any algorithm to find the median of n keys(for odd n) by comparison of keys must do at least 3n/2-3/2 comparisons in the worst case.
- **Argument:**
  - There must be done n-1 crucial comparisons at least.
  - An adversary can force the algorithm to perform as many as $(n\text{-}1)/2$ noncrucial comparisons.
    - Note: the algorithm can always start out by doing $(n\text{-}1)/2$ comparisons involving 2 N-keys, so, only (n-1)/2 L or S left for the adversary to assign freely as the adversary rule.

Thank you!

Q & A

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