

DSC 40B

Theoretical Foundations II

Lecture 7 | Part 1

The Median and Order Statistics

The Median

- ▶ How fast can we find a **median** of n numbers?

Algorithms

- ▶ We have seen several ways of computing a median:
 - ▶ Alg. 1: Minimize absolute error, brute force.
 - ▶ Alg. 2: Use definition ($\text{half} \leq$, $\text{half} \geq$).
 - ▶ ...

Exercise

Using what we know so far, what approach for finding the median has the best **worst-case time complexity**?

Best so far...

- ▶ Sort the list with mergesort, return middle element.
- ▶ Time complexity: $\Theta(n \log n)$.

Is sorting necessary?

- ▶ Need to sort the whole list just to find middle?
- ▶ Seems like more work than necessary.

Today

- ▶ We'll design an algorithm which runs in $\Theta(n)$ expected time.
- ▶ Much more useful than just finding median...

Order Statistics

- The median is an example of an **order statistic**.

Definition

Given n numbers, the **k th order statistic** is the k th smallest number in the collection.

Example

[99, 42, -77, -12, 101]

- ▶ 1st order statistic:
- ▶ 2nd order statistic:
- ▶ 4th order statistic:

Exercise

Some special cases of order statistics go by different names. Can you think of some?

Special Cases

- ▶ **Minimum:** 1st order statistic.
- ▶ **Maximum:** n th order statistic.
- ▶ **Median:** $\lceil n/2 \rceil$ th order statistic¹.
- ▶ **p th Percentile:** $\lceil \frac{p}{100} \cdot n \rceil$ th order statistic.

¹What if n is even?

Goal

- ▶ **Fast** algorithm for computing any order statistic.
- ▶ Interestingly, some seem easier than others.
- ▶ Our algorithm will find **any** order statistic in $\Theta(n)$ *expected* time.

Approach #1

- ▶ We can modify `selection_sort` to find the k th order statistic.
- ▶ Loop invariant: after k th iteration, first k elements are in final sorted order.

```
def selection_sort(arr):  
    """In-place selection sort."""  
    n = len(arr)  
    if n <= 1:  
        return  
    for barrier_ix in range(n-1):  
        # find index of min in arr[start:]  
        min_ix = find_minimum(arr, start=barrier_ix)  
        #swap  
        arr[barrier_ix], arr[min_ix] = (  
            arr[min_ix], arr[barrier_ix]  
        )
```

```
def select_k(arr, k):  
    """Find kth order statistic."""  
    n = len(arr)  
    if n <= 1:  
        return  
    for barrier_ix in range(k):  
        # find index of min in arr[start:]  
        min_ix = find_minimum(arr, start=barrier_ix)  
        #swap  
        arr[barrier_ix], arr[min_ix] = (  
            arr[min_ix], arr[barrier_ix]  
        )  
    return arr[k-1]
```

Exercise

What are the best case and worst case time complexities of `select_k`?

Approach #1

- ▶ 1st order statistic: $\Theta(n)$.
- ▶ n th order statistic: $\Theta(n^2)$.
- ▶ Median: $\Theta(n^2)$.
- ▶ k th order statistic: $\Theta(kn)$.

Exercise

Describe how to find any order statistic in $\Theta(n \log n)$ time.

Approach #2

- ▶ Sort with mergesort, return `arr[k-1]`
- ▶ $\Theta(n \log n)$ time. Could be better...

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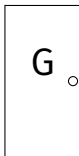
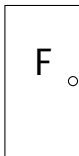
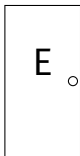
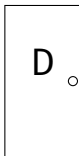
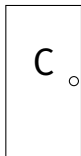
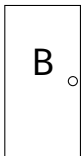
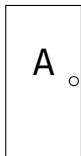
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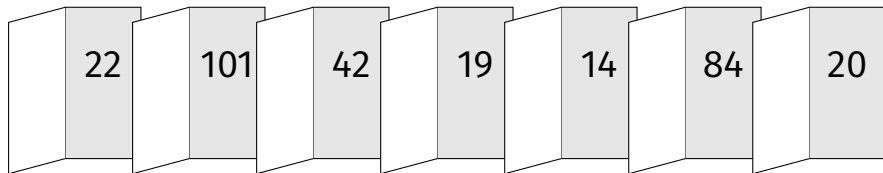
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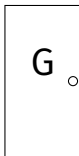
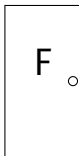
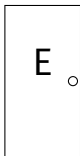
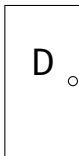
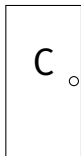
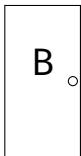
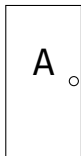
Quickselect

The Goal

- ▶ Given a collection of n numbers and an order, k .
- ▶ Find the k th smallest number in the collection.

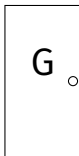
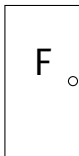
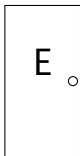
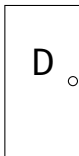
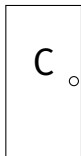
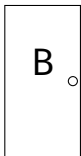
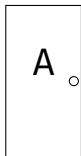


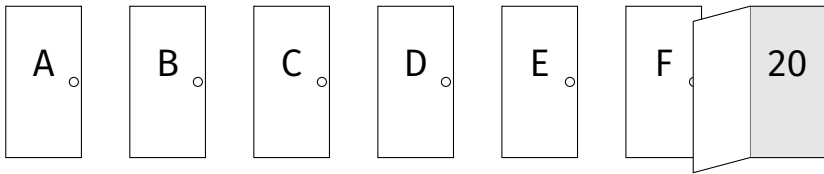


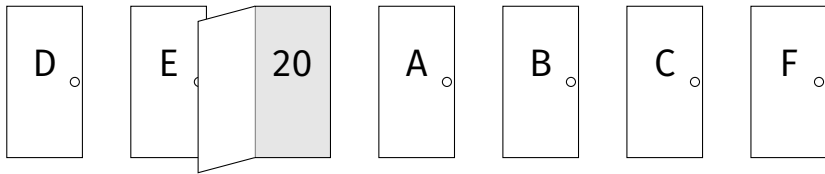


Game Show

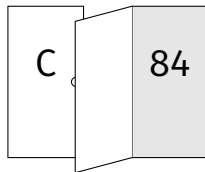
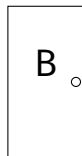
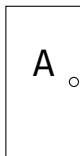
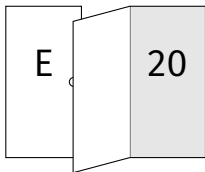
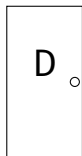
- ▶ **Goal:** tell the host the **largest** number.
- ▶ **Caution:** with every door opened, your money is reduced.
- ▶ **Twist:** After opening a door, the host tells you:
 - ▶ which doors are smaller.
 - ▶ which doors are larger.
 - ▶ they **partition** the doors into higher and lower by moving them.

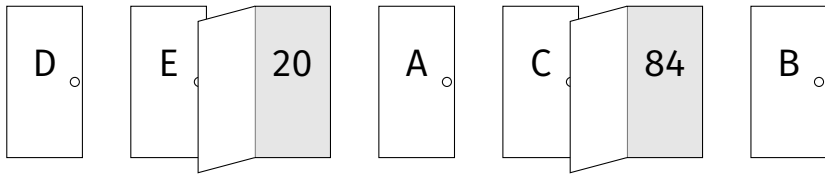




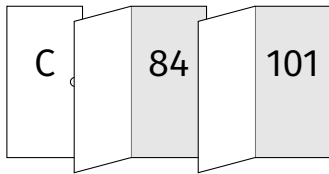
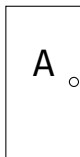
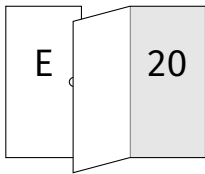


after partitioning





after partitioning



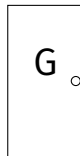
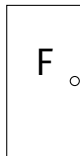
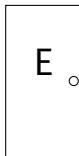
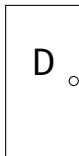
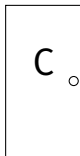
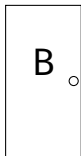
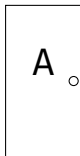
Main Idea

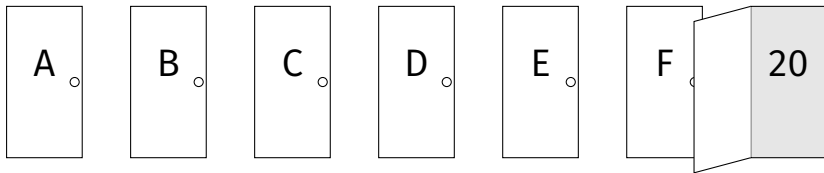
After partitioning, the just-opened door is in the **correct place** in the sorted order (but the other doors may not be).

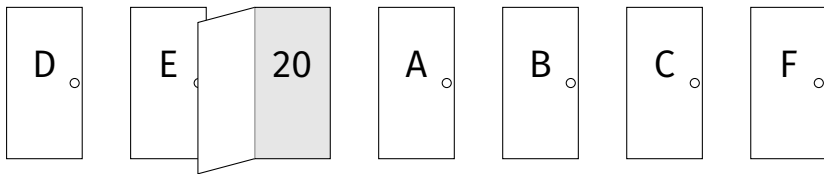
But, every door to the left is smaller (\leq), every door to the right is larger (\geq).

In general...

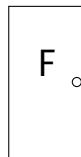
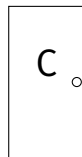
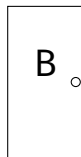
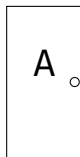
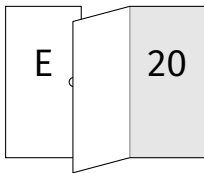
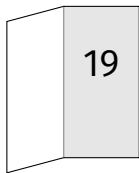
- ▶ Let's generalize strategy for k th order statistic.
- ▶ Example: $k = 2$.

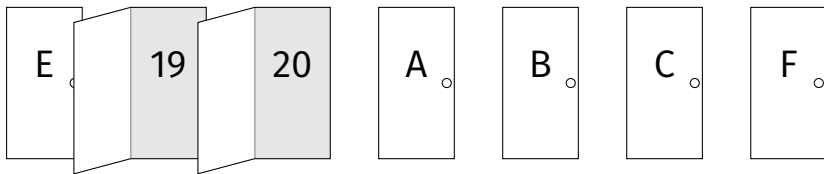






after partitioning





after partitioning

Strategy

- ▶ Open arbitrary door (that hasn't been ruled out).
- ▶ **Partition** the doors around this number:
 - ▶ Move doors smaller than this to the left,
 - ▶ Larger than this to the right.
- ▶ Let p be our door's new position, k be the order we want.
 - ▶ If $p = k$, return this door.
 - ▶ If $p < k$, rule out doors to left.
 - ▶ If $p > k$, rule out doors to right.
- ▶ Repeat.

In Code

```
import random
def quickselect(arr, k, start, stop):
    """Finds kth order statistic in numbers[start:stop)"""
    pivot_ix = random.randrange(start, stop)
    pivot_ix = partition(arr, start, stop, pivot_ix)
    pivot_order = pivot_ix + 1
    if pivot_order == k:
        return arr[pivot_ix]
    elif pivot_order < k:
        return quickselect(arr, k, pivot_ix + 1, stop)
    else:
        return quickselect(arr, k, start, pivot_ix)
```


Example

`arr = [77, 42, 11, 99, 0, 101]` `k = 3`

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Theoretical Foundations II

Lecture 7 | Part 3

Partition

Partitioning

- ▶ Given an array of n numbers and the index of a **pivot** p .
- ▶ Rearrange elements so that:
 - ▶ Everything $< p$ is first.
 - ▶ Everything $= p$ is next.
 - ▶ Everything $> p$ is last.
- ▶ Return index of first element $\geq p$.

```
def partition(arr, start, stop, pivot_ix):  
    """Partition arr[start:stop] around pivot."""  
    left = []  
    pivot_count = 0  
    right = []  
    pivot = arr[pivot_ix]  
    for ix in range(start, stop):  
        if arr[ix] < pivot:  
            left.append(arr[ix])  
        elif arr[ix] == pivot:  
            pivot_count += 1  
        else:  
            right.append(arr[ix])  
    ix = start  
    for x in left:  
        arr[ix] = x  
        ix += 1  
    for i in range(pivot_count):  
        arr[ix] = pivot  
        ix += 1  
    for x in right:  
        arr[ix] = x  
        ix += 1  
    return start + len(left)
```

Partition

- ▶ partition takes $\Theta(n)$ time.
 - ▶ This is **optimal**.
- ▶ But we can use memory more efficiently.

Motivation

- ▶ Similar to selection sort, we'll use **two** barriers:
- ▶ **“Middle”** barrier:
 - ▶ Separates things $<$ pivot from things \geq
 - ▶ Index of first thing in “right”
- ▶ **“End”** barrier:
 - ▶ Separates processed from processed.
 - ▶ Index of first “unprocessed” thing.



Example

Simplification: start by moving pivot to end.

```
arr = [77, 42, 11, 99, 0, 101]    pivot_ix = 1
```

Loop Invariants

- ▶ After each iteration:
 - ▶ everything in `arr[start:middle_barrier]` is $<$ pivot.
 - ▶ everything in `arr[middle_barrier:end_barrier]` is \geq pivot.
 - ▶ everything in `arr[end_barrier:stop]` is “unprocessed”


```
def in_place_partition(arr, start, stop, pivot_ix):  
    def swap(ix_1, ix_2):  
        arr[ix_1], arr[ix_2] = arr[ix_2], arr[ix_1]  
  
    pivot = arr[pivot_ix]  
    swap(pivot_ix, stop-1)  
    middle_barrier = start  
    for end_barrier in range(start, stop - 1):  
        if arr[end_barrier] < pivot:  
            swap(middle_barrier, end_barrier)  
            middle_barrier += 1  
        # else:  
        # do nothing  
    swap(middle_barrier, stop-1)  
    return middle_barrier
```

Efficiency

- ▶ Also takes $\Theta(n)$ time.
- ▶ No auxiliary memory required.

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Theoretical Foundations II

Lecture 7 | Part 4

Time Complexity Analysis

Time Complexity

- ▶ What is time complexity of quickselect?

```
import random
def quickselect(arr, k, start, stop):
    """Finds kth order statistic in numbers[start:stop)"""
    pivot_ix = random.randrange(start, stop)
    pivot_ix = partition(arr, start, stop, pivot_ix)
    pivot_order = pivot_ix + 1
    if pivot_order == k:
        return arr[pivot_ix]
    elif pivot_order < k:
        return quickselect(arr, k, pivot_ix + 1, stop)
    else:
        return quickselect(arr, k, start, pivot_ix)
```

Problem

- ▶ We don't know the size of the subproblem.
 - ▶ Is random, can be anywhere from 1 to $n - 1$.
- ▶ Difficult to write recurrence relation.

Good and Bad Pivots

- ▶ Some pivots are better than others.
 - ▶ **Good**: splits array into roughly balanced halves.
 - ▶ **Bad**: splits array into wildly unbalanced pieces.

Exercise

Suppose we're searching for the minimum. What would be the worst possible pivot?

Worst Case

- ▶ Suppose we're searching for $k = 1$ (minimum).
- ▶ Worst pivot: the maximum.
- ▶ Worst case: use max as pivot every time.
- ▶ Subproblem size: $n - 1$.

Worst Case

- ▶ Every recursive call is on problem of size $n - 1$.
- ▶ $T(n) = T(n - 1) + \Theta(n)$.
 - ▶ Solution: $\Theta(n^2)$.
- ▶ Intuitively, randomly choosing largest number as pivot every time is **very** unlikely!

$$\frac{1}{n} \times \frac{1}{n-1} \times \frac{1}{n-2} \times \dots \times \frac{1}{3} \times \frac{1}{2} = \frac{1}{n!}$$

Equally Unlikely

- ▶ Pivot falls exactly in the middle, every time.
- ▶ Subproblems are of size $n/2$.
- ▶ $T(n) = T(n/2) + \Theta(n)$.
 - ▶ Solution: $\Theta(n)$.

Typically

- ▶ Pivot falls somewhere in the middle.
- ▶ Sometimes **good**, sometimes **bad**.
- ▶ But **good** pivots reduce problem size by **so much** that they make up for **bad** pivots.

Analogy

- ▶ You're 100 miles away from home.
- ▶ You have a button that, if you press it, teleports you **1 mile** closer to home.
- ▶ How many times must you press it before you're 1 mile away from home?

Analogy

- ▶ You're 100 miles away from home.
- ▶ You have a button that, if you press it, teleports you **1 mile** closer to home.
- ▶ How many times must you press it before you're 1 mile away from home?
 - ▶ **Answer:** 99 times.

Analogy

- ▶ You're 100 miles away from home.
- ▶ You have a button that, if you press it, teleports you **half the distance** to home.
- ▶ How many times must you press it before you're <1 mile away from home?

Analogy

- ▶ You're 100 miles away from home.
- ▶ You have a button that, if you press it, teleports you **half the distance** to home.
- ▶ How many times must you press it before you're <1 mile away from home?
 - ▶ **Answer:** *about* $\log_2 100 \approx 6.64$ times.

Analogy

- ▶ You're 100 miles away from home.
- ▶ You have a button that, if you press it, teleports you **half the distance** to home with probability $1/2$, does nothing with probability $1/2$.
- ▶ How many times do you **expect** to press it before you're <1 mile away from home?
 - ▶ **Answer:** *about* twice as many times as before. So, $2 \log_2 100 \approx 13.28$.

Analysis

- ▶ We'll call a pivot **good** if it falls in the middle half of the array.
 - ▶ Probability: $1/2$
 - ▶ Max recursive problem size: $3n/4$.
- ▶ We'll call a pivot **bad** if it falls outside of the middle half.
 - ▶ Probability: $1/2$
 - ▶ Max recursive problem size: $n - 1$.

(Very) Hand-Wavy Analysis

- ▶ If we're **guaranteed** a good pivot, we'd have:
 - ▶ $T(n) \leq T(3n/4) + \Theta(n)$.
 - ▶ Solution: $\Theta(n)$.
- ▶ If we only get a good pivot **half** the time, we expect to make **twice** as many recursive calls.
- ▶ And so we expect to take about twice as long.
 - ▶ But $2\Theta(n)$ is still $\Theta(n)$.

Quickselect

- ▶ Expected time complexity: $\Theta(n)$.
- ▶ Worst case: $\Theta(n^2)$, but **very unlikely**.

Median

- ▶ We can find the median in expected linear time with **quickselect**.

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Theoretical Foundations II

Lecture 7 | Part 5

Quicksort

Last Time

- ▶ We saw mergesort.
- ▶ **Divide:** split list directly down the middle
- ▶ **Conquer:** sort each half
- ▶ **Combine:** merge sorted halves together

merge does all the work

- ▶ In mergesort, we are lazy when we divide.
- ▶ So we have to work to combine.

$[4, 1, 3, 2] \rightarrow [4, 1], [3, 2] \rightarrow [4, 3], [2, 3] \rightarrow [1, 2, 3, 4]$

What if?

- ▶ Suppose we divide so that everything in `left` is smaller than everything in `right`:
- ▶ After sorting, no need for merge.
- ▶ `[5,1,3,8,6,2] → [1,3,2],[5,8,6]`

What if?

- ▶ Suppose we divide so that everything in `left` is smaller than everything in `right`:
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- ▶ This is what `partition` does!

Quicksort

```
def quicksort(arr, start, stop):  
    """Sort arr[start:stop] in-place."""  
    if stop - start > 1:  
        pivot_ix = random.randrange(start, stop)  
        pivot_ix = partition(arr, start, stop, pivot_ix)  
        quicksort(arr, start, pivot_ix)  
        quicksort(arr, pivot_ix+1, stop)
```

Time Complexity

- ▶ Average case: $\Theta(n \log n)$
- ▶ Worst case: $\Theta(n^2)$.
- ▶ Like with quickselect, worst case is **very rare**.

Mergesort vs Quicksort

- ▶ Mergesort has better worst case complexity.
- ▶ But in practice, Quicksort is often faster.
- ▶ Takes less memory, too.

Memory Requirements

- ▶ merges requires output array, $\Theta(n)$ additional space.
- ▶ partition works in-place, requires no additional space²
- ▶ Example: sorting 3 GB of data with 4 GB of RAM.

²Call stack for quicksort requires $\Theta(\log n)$ additional space.